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Groundwater in the Inner Bluegrass Karst Region, Kentucky

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GROUNDWATER IN THE INNER BLUEGRASS KARST REGION, KENTUCKY

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ABSTRACT

The hydrogeology of about 12% of the 5600 km^2 Inner Bluegrass Karst Region of central Kentucky was investigated by water tracing and other techniques. Using fluorescent dyes adsorbed on fabric and charcoal detectors, 96 traces (average length 2.7 km, maximum length 15 km) resulted in the identification of 38 groundwater basins (with areas up to 15 km^2). Within the basins, subsurface flow is in a dendritic conduit system at depths up to 30 m below the surface, while in the interbasin areas which separate them flow is generally less than 5 m deep. Each groundwater basin discharges at a spring whose median discharge is approximately 20 $l/s \cdot km^2$ of basin area. The largest spring (Royal Spring) in the study area has a median discharge greater than 300 l/s (Meinzer second magnitude).

The Ordovician Lexington Limestone which underlies the region is thin bedded with shale partings and argillaceous units. Within groundwater basins, sinkhole drains and other conduits have breached the interbedded shales and descend nearly vertically to a level determined by equilibrium flow in the larger conduits. The general location and flow directions in groundwater basins is probably determined by a potentiometric gradient prior to conduit development, and some basins are localized by a favorably oriented regional joint set or other structural element. Otherwise, lithologic and structural factors have little influence in the occurrence and flow of subsurface water in the region.

Descriptors: Karst Hydrology *, Groundwater Movement *, Groundwater Basins *, Dye Releases *, Aquifers, Groundwater, Groundwater Pollution, Karst, Limestone, Springs.

Identifiers: Inner Bluegrass Karst Region, Kentucky, Ordovician.

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Appreciation is also expressed to the literally hundreds of land owners, farm managers, and others for permitting access to their property and furnishing information in the field. It is regretted that space does not allow them to be individually listed. Finally, thanks are extended to C.D. Irvine and M.A. Palmer of the Department of Geology for their assistance in the preparation of this report, and to R.R. Huffsey, Assistant Director of the Kentucky Water Resources Research Institute, for his help and support throughout the conduct of the project.

DISCLAIMER

TABLE OF CONTENTS

ABSTRACT.. ii

ACKNOWLEDGEMENTS.. iii

DISCLAIMER.. iii

TABLE OF CONTENTS... iv

LIST OF TABLES..viii

LIST OF ILLUSTRATIONS.....................................viii

A. INTRODUCTION.. 1

A1. Project Objectives...................................... 1

A2. Organization and Use of this Report..................... 2

A3. The Inner Bluegrass Karst Region........................ 7

A3a. Geologic Structure..................................... 8

A3b. Stratigraphy... 9

A3c. Previous Hydrogeologic Investigations.................. 11

A4. Methods... 14

A4a. Field Reconnaissance................................... 15

A4b. Dyes and Detectors..................................... 15

A4c. Discharge Observations and Spring Magnitude Determination.. 17

A4d. Data Management.. 19

B. NORTHEAST WOODFORD COUNTY AREA (McCann and Thrailkill)... 22

B1. Groundwater Basins...................................... 22

B1a. Roaring Spring Basin (28).............................. 22

B1b. Other Basins: Spring 13 (44), Pin Oak Spring (26), Versailles Spring (47).................................. 23

B2. Discussion.. 24

B2a. Nature of Groundwater Basins........................... 24

B2b. Effect on Northern Woodford County Groundwater from Versailles Area Development............................ 25

B2c. Factors Influencing Subsurface Flow and Groundwater Basins.. 25

C. MERCER COUNTY AREA (Hopper and Thrailkill)............... 27

C1. Groundwater Basins...................................... 27

C1a. Big Spring Basin (3)................................... 27

C1b. Burgin Spring Basin (8)................................ 28

C1c. Distillery Spring Basin (12) 29
C1d. Shawnee Run Spring Basin (34) 30
C1e. Hartman Spring Basin (17) 30
C1f. Shawnee Copperhead Spring Basin (32) 30
C1g. Cove Spring Basin (11) 31
C1h. Baker Cave Spring Basin (2) 32
C1i. Other Basins: Votah Spring (48), Humane Spring (19), Eureka Spring (14), Duvall Cave (C16), Railroad Spring (27) 32
C2. Discussion 33
C2a. Nature of Groundwater Basins 33
C2b. Influence of Structural Factors 34
C2c. Influence of Lithology 35
D. NORTHERN FAYETTE AND SOUTHERN SCOTT COUNTIES AREA (Spangler, Troester, and Thrailkill) 38
D1. Groundwater Basins 38
D1a. Royal Spring Basin (29) 38
D1b. Russell Cave Spring Basin (30) 40
D1c. Vaughans Spring Basin (46) 42
D1d. Lindsay Spring (22) and Spring Lake Spring (40) Basins 42
D1e. Silver Springs Basin (35) 43
D1f. Slacks Spring Basin (36) 44
D1g. Gano Spring Basin (15) 45
D1h. Nance Spring Basin (24) 46
D1i. Smaller North Elkhorn Creek Basins: Sharp Swallet (B3), Holland Spring (18), Tevis Spring (43) 46
D1j. Smaller South Elkhorn Creek Basins: Ansley Swallet (D57), Santen Spring (31), Elkhorn Spring (13), Cornett Spring (10) 47
D1k. Other Basins: Jennings Spring (21), Steeles Spring (41), Blue Spring (4) 48
D2. Discussion 48
D2a. Relationship Between Surface and Subsurface Flow 49
D2b. Influence of Structural Factors 49

D2c. Control of Subsurface Flow by Argillaceous Units.. 50
D2d. Nature of Groundwater Basins.................... 51
E. WALNUT HILL AREA (Gouzie and Thrailkill)................ 53
E1. Groundwater Basins.................................. 53
E1a. Boggs Spring Basin (5)........................... 53
E1b. I-75 Pond Spring Basin (20)...................... 53
E2. Discussion.. 53
F. SUBSURFACE WATER IN THE INNER BLUEGRASS KARST REGION (Thrailkill).. 55
F1. Groundwater Basins.................................. 55
F1a. Basin Identification, Size, and Location........ 56
F1b. Interbasin Areas and Basin Shape................ 59
F2. Basin Area and Spring Discharge..................... 61
F3. Groundwater Basins and Karst Landforms.............. 63
F3a. Sinkhole Origin.................................. 64
F3b. Sinkhole Filling and Map Inadequacy............. 67
F4. Groundwater Basins and Wells........................ 68
F4a. Georgetown Quadrangle........................... 69
F5. Contaminant Transport............................... 73
F5a. Destination of Contaminants..................... 73
F5b. Source of Detected Contaminants................. 74
F5c. Well Contamination.............................. 75
F5d. Flow and Other Parameters....................... 76
F6. Geologic and Other Factors Influencing Subsurface Flow and Groundwater Basin Development............... 77
F6a. Lithology of Stratigraphic Units................ 77
F6b. Bedding Attitude................................ 79
F6c. Faults, Joints, Sinkhole Trends, and Similar Features.. 80
F6d. Topography...................................... 84
F6e. Geomorphology................................... 85
F6f. Conclusions and Utility of Geologic Maps........ 85
F7. Nature and Development of the Hydrogeologic System... 86
F7a. Types of Flow................................... 87
F7b. The Non-Meteoric System......................... 89

F7c. Conduit Initiation.............................. 90
F7d. Stages in Conduit Growth........................ 93
F7e. Groundwater Basins, Interbasin Areas, and the Aquifer.. 95
F7f. Influence of Human Activities.................. 97
F8. Groundwater Availability............................ 98
F9. Applicability of Findings to Other Karst Areas....... 101
REFERENCES.. 104
APPENDIX 1: RESULTS OF DYE TRACES..........................A1-1
APPENDIX 2: SPRING LOCATIONS AND DYE INTRODUCTIONS..........A2-1
APPENDIX 3: NEGATIVE DYE DETECTION........................A3-1
APPENDIX 4: SPRING DISCHARGES...............................A4-1
APPENDIX 5: GEORGETOWN QUADRANGLE WELL DATA................A5-1
APPENDIX 6: UNIT CONVERSIONS................................A6-1

LIST OF TABLES

1. Stratigraphic units in the study area.................... 11
2. Springs and groundwater basins in the study area.........19-21
3. Sub-parallel groundwater basins.......................... 82
4. Types of subsurface flow................................. 90

LIST OF FIGURES

1. Map of Inner Bluegrass Karst Region..................... 3
2. Groundwater basins in the Northeast Woodford County area and western portion of the Northern Fayette and Southern Scott counties area.................................. 4
3. Groundwater basins in the Mercer County area............. 5
4. Groundwater basins in the eastern portion of the Northern Fayette and Southern Scott Counties area and the Walnut Hill area.................................. 6
5. Map showing relationship of groundwater basins to surface streams and surface divides......................57
6. Cross section of groundwater basins and interbasin areas...58
7. Relationship between groundwater basin area and median discharge of springs..................................62
8. Types of sinkholes.....................................66
9. Map of Georgetown quadrangle showing satisfactory and unsatisfactory wells....................................71
10. Map of Georgetown quadrangle showing potentiometric surface contours......................................72

A. INTRODUCTION

This is the first of two Completion Reports for Project B-064-KY, Hydrogeology of the Inner Bluegrass Karst Region, Kentucky: Water Tracing Studies, which was funded by the Office of Water Research and Technology, U.S. Dept. of the Interior. It includes both the specific results of water tracing and related studies in portions of the region, and a discussion of the nature of subsurface flow in the region. In order to present the results of the overall Inner Bluegrass Karst Project to date, information whose collection was funded by other sources is included.

The second Completion Report for Project B-064-KY is in preparation. It will include the results of a variety of investigations, including dye research and quantitative tracing experiments, which were undertaken because of other project objectives or to support area studies herein reported. It is cited in the present report as Thrailkill, et. al (in preparation).

A1. Project Objectives

The objectives of the project were:

(a) To delineate, by qualitative and semi-quantitative dye-tracing techniques, major underground flow connections and groundwater divides in specific areas within the Inner Bluegrass Karst Region ("Area Studies").

This Completion Report describes the results of work done to support this objective.

(b) To undertake quantitative dye studies of selected paths to determine hydrologic parameters ("Quantitative Traces").

(c) To perform laboratory and field investigations to discover the most suitable dyes and dye-detector combinations ("Dye Investigations").

(d) In support of these objectives, certain other tasks may be performed ("Other Work").

The results of work to support these objectives are in the second Completion Report.

A2. Organization and Use of this Report

Many readers of this report will be concerned primarily with a specific local area, and the following is provided to assist such a reader. Figure 1 is a map of the Inner Bluegrass Karst Region which shows the coverage of the larger scale maps (Fig. 2-4) of the areas studied. Inspection of the appropriate area map should indicate whether the specific area of interest in located in a delineated groundwater basin, an adjacent interbasin area, or is in a portion of the area covered by the map which has not been studied.

If the location falls on one of the area maps but is outside the area in which dye traces were conducted, the Discussion Section of the report section dealing with the nearby study area may contain information of interest. A discussion of subsurface water in the region as a whole will be found in Section F, which may be useful in evaluating specific locations which lie outside (as well as within) the coverage of the area maps (Fig. 2-4). Portions of Section F deal with particular aspects of subsurface water in the region, such as availability (Section F8) and contaminant transport (Section F5).

If the location is within or near a groundwater basin outlined on Fig. 2-4, the name of the discharging spring can be found in Table 2 using the number shown on the map. The section of the report in which the groundwater basin is discussed is also given in Table 2. Dye introduction points for traces to the spring are labeled on Fig. 2-4 by the dye introduction number of the first successful trace.

The area maps (Fig. 2-4) are of such small scale that it may not be possible to determine the position of a specific location of interest relative to springs or dye inputs with sufficient accurracy. Because it was not possible to include in this report the many larger scale maps that might be needed, it is recommended that the appropriate topographic map of the area be obtained, and the locations of dye inputs and springs in the vicinity of the area of interest be transferred to it.

A contraction at the name of the 7.5 minute 1:24000 quadrangle is shown on Fig. 2-4, and the full name is given in the explanation for Appendix 1. Spring locations in LT coordinates are listed in Appendix 2. Appendix 1 is a tabulation of all dye introductions arranged by dye introduction number, and contains the location of the input point and

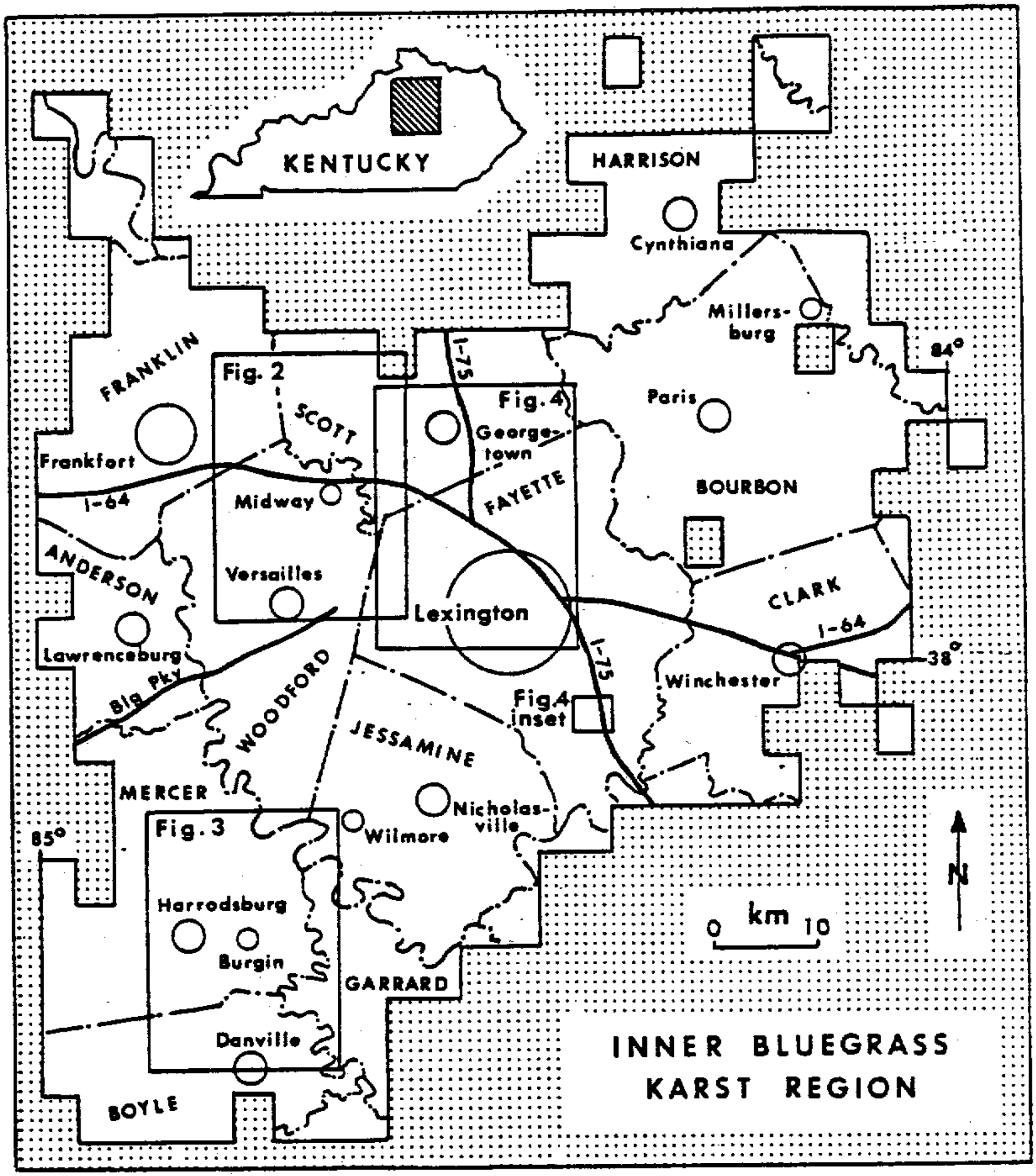

Figure 1. Map of Inner Bluegrass Karst Region showing coverage of Fig. 2, 3, and 4. Note index map in upper left.

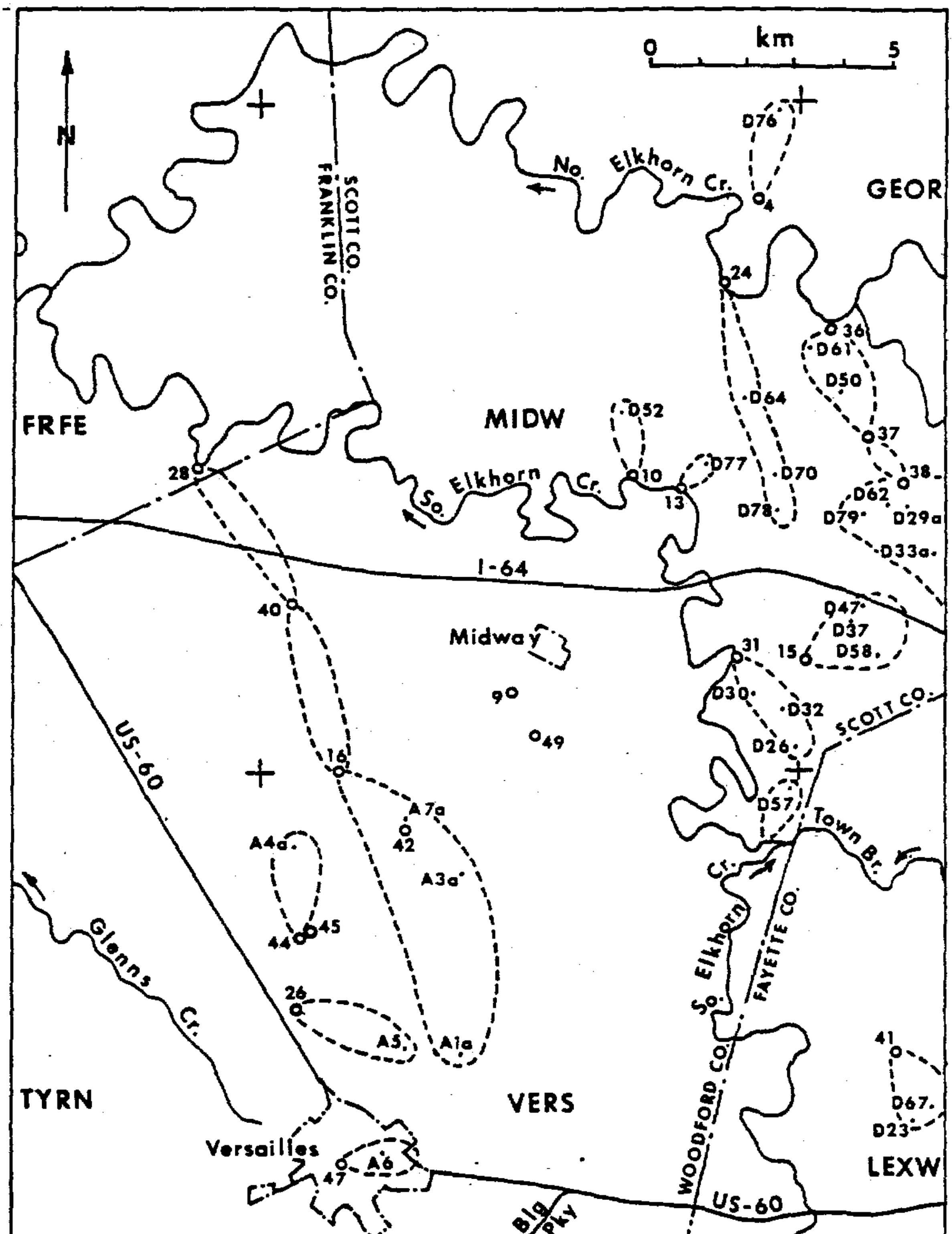

Figure 2. Groundwater basins (dashed outlines) in the Northeast Woodford County area and the western portion of the Northern Fayette and Southern Scott counties area. Open circles are springs (Table 2) and points are dye introductions (Appendix 1). Quadrangle names contracted to four letters.

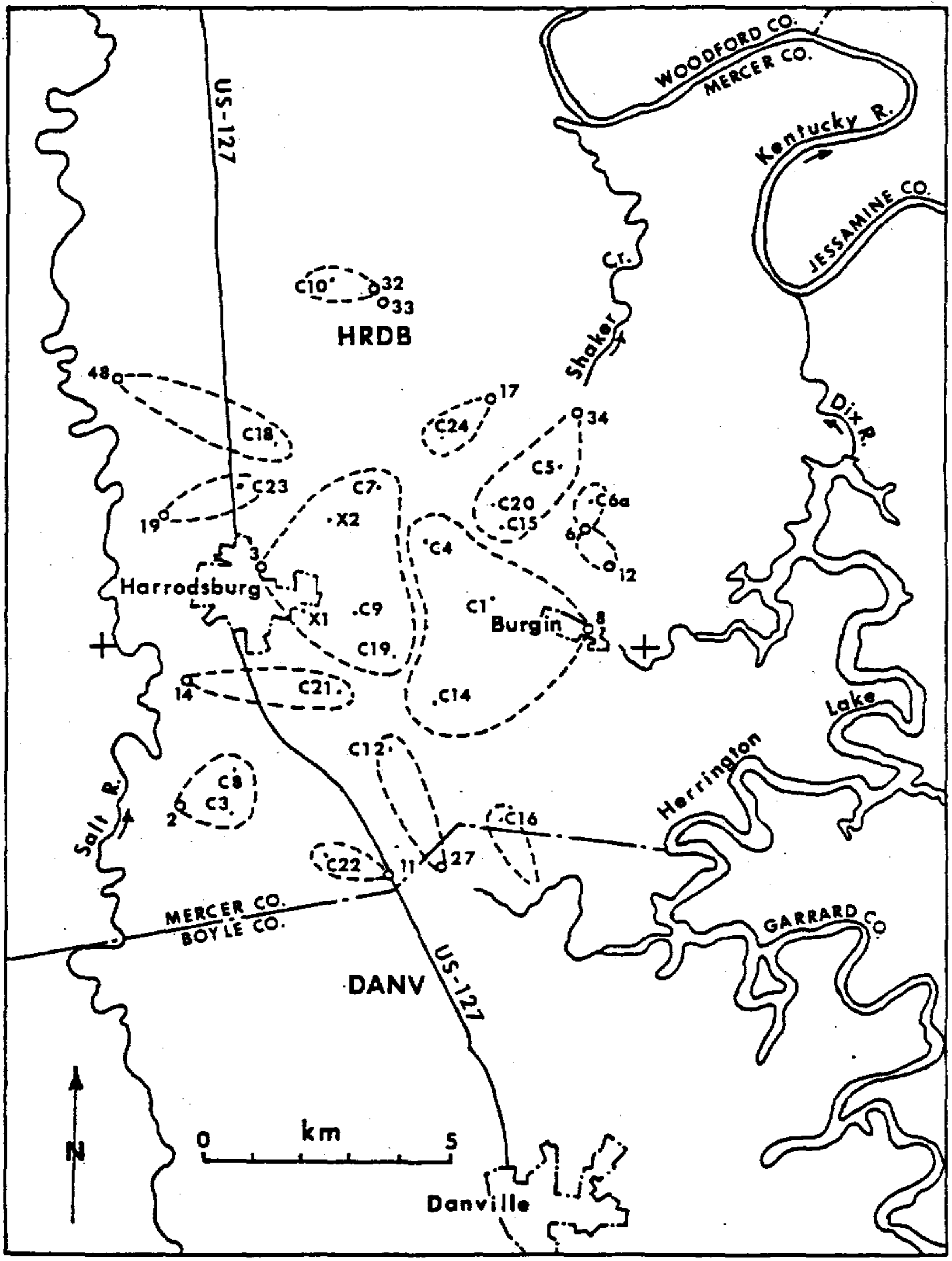

Figure 3. Groundwater basins in the Mercer County area. See Fig. 2 for explanation (and section C1a for discussion of points X1 and X2).

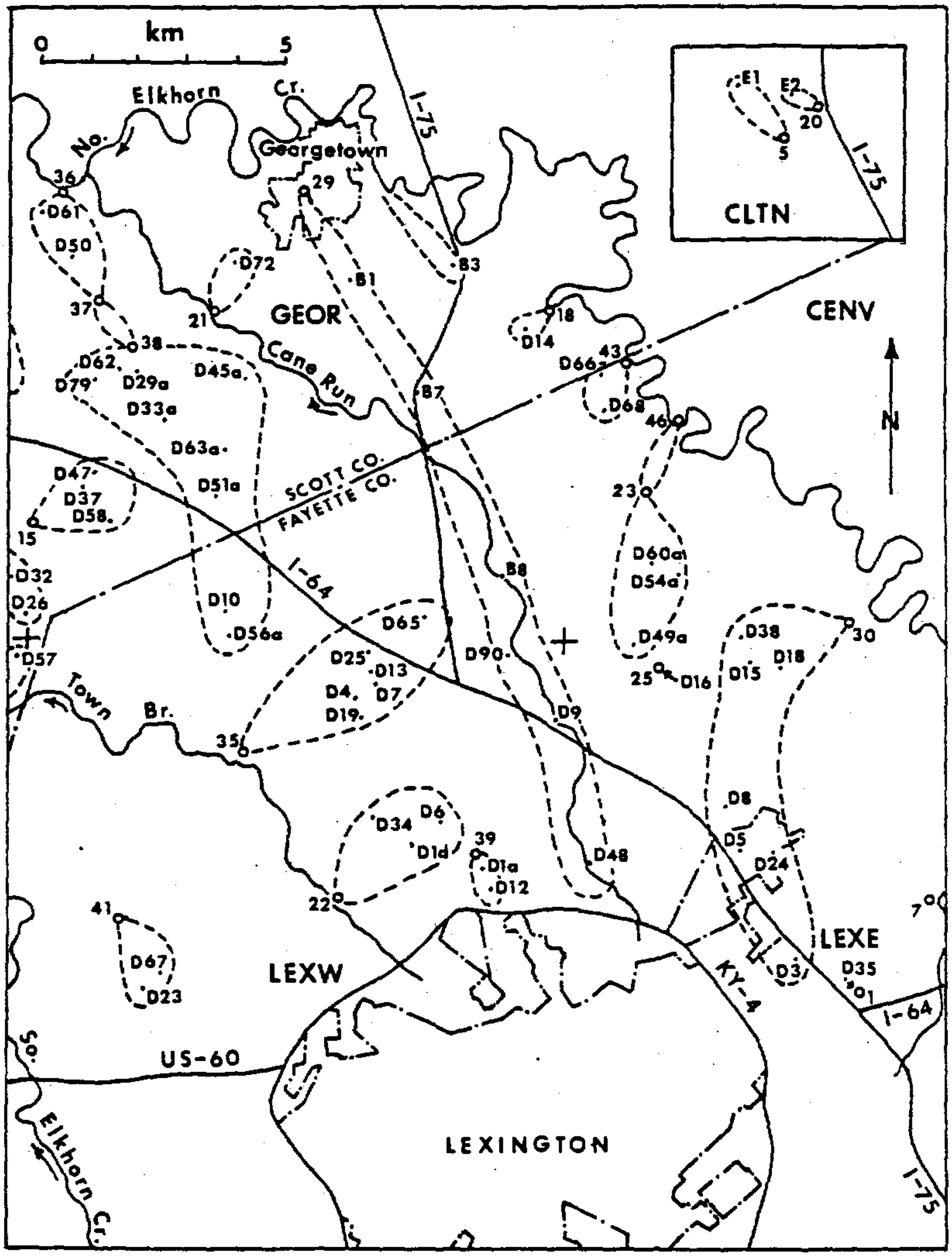

Figure 4. Groundwater basins in the eastern portion of the Northern Fayette and Southern Scott counties area and the Walnut Hill area (inset map in upper right). See Fig. 2 for explanation. Arrow between dye introduction point and spring is trace in an interbasin area.

detection point in LT coordinates (lines 4-5 and 9-10, respectively).

The so-called LT location system was found to be faster to use and less subject to error than the more familiar latitude and longitude system. LT coordinates consist of two letter groups followed by two numbers. The first letter group is a contraction of the 7.5 minute quadrangle name (listed in the explanation for Appendix 1), and the second identifies one of the nine 2.5 minute quadrangles within the larger quadrangle indicated by tick marks on the margin and within the map area. The code for this identifer (usually obvious) is also given in the explanation for Appendix 1. The first number is the map distances in inches east of the west boundary at the 2.5 minute quadrangle, and the second is the distance north of the south boundary. Thus dye introduction point Ala with coordinates: VERS CC 0.55 5.60 is on the Versailles (VERS) 7.5 minute quadrangle, in the center (CC) 2.5 minute quadrangle, and 0.55 inches east and 5.60 inches north of the southwest corner of this 2.5 minute quadrangle.

Coordinates given in the LT system are readily convertible into latitude and longitude, as discussed in Appendix 6. Other than the use of inches in the LT system, all other measurements in this report are in metric (SI) units, which may be converted to more familiar units using factors also given in Appendix 6.

Information on dye introductions which did not result in traces, as well as travel times and other data for individual dye introductions listed in Appendix 1, may be useful in investigations of specific areas, and Appendix 2 lists all dye introductions made in and near each groundwater basin. Finally, springs and other flows monitored during a trace in which dye was not detected are listed in Appendix 3. Although this information is incomplete, it may be of value if evidence on the absence of a subsurface flow connection is wanted.

A3. The Inner Bluegrass Karst Region

The Inner Bluegrass Karst Region is an area of about 5600 square kilometers in central Kentucky. It is largely a gently rolling upland at an altitude of about 250 m with generally less than 50 m of local relief, which has been termed the Lexington Peneplain (Jillson, 1961). Most of the streams which drain the area are on the upland, but the Kentucky River, which crosses the region, has incised a gorge more than 100 m deep.

Altitudes range from about 350 m in the southeastern portion of the upland to 130 m along the Kentucky River where it leaves the region in the northwest.

Although the streams on the upland surface appear to provide normal surface drainage, numerous karst landforms (especially sinkholes) are present, and portions of the region, some with areas in excess of 10 km^2, have no surface drainage. The outlines of the region were defined (Fig. 1) by including within its boundaries all 2.5-minute quadrangles (1:24-000) which depict at least one sinkhole by topographic contours (interval 3.0 or 6.1 m) in rocks of middle Ordovician age. The Inner Bluegrass Karst Region is both geographically and stratigraphically distinct from another extensive karst area (a portion of which has been termed the Central Kentucky Karst) in Mississippi rocks, as well as from smaller karst areas in Kentucky in upper Ordovician and Silurian rocks.

The mean annual precipitation is about 1150 mm fairly evenly distributed throughout the year. Mean July and January temperatures are about 25 and 0°, respectively. The regolith is often a meter or more thick and is generally considered to be residual. The entire region is south of the area modified by Pleistocene glaciation. The present population is in excess of 350,000, of which more than one-half is concentrated at Lexington, the second largest city in Kentucky, which lies near the center of the region (Fig. 1).

A3a. Geologic Structure

The region occupies the area where carbonate rocks of middle Ordovician age have been exposed by erosion on the crest of the Cincinnati ARch, a regional structural feature of the eastern United States. Regional dip is generally away from the highest point on the arch in Jessamine County (Fig. 1) in all directions except to the southeast, where the rocks have been down faulted. Regional dip is gentle (on the order of 10 m/km), and the beds seen in outcrops generally appear nearly horizontal.

The southeast boundary of the region follows the Lexington Fault System in the south and the intersecting Kentucky River Fault System to the east (Black, et. al., 1977). The east and south sides of these fault systems are downdropped, and unkarstified upper Ordovician limestones and shales cover the middle Ordovician carbonates.

There are a few areas of substantial faulting within the region, such as the Switzer Graben in Scott County and the extension of the Lexington Fault System to the north. There are also a number of short, high-angle faults and mineralized veins.

A3b. Stratigraphy

The boundaries of the region approximately coincide with the depositional or fault contact of relatively pure lower Ordovician carbonates with the overlying thinly interbedded upper Ordovician limestones and shales. The overlying limestones and shale sequence has been designated the Clays Ferry Formation, and the underlying carbonates are, from highest to lowest, the Lexington Limestone, Tyrone Limestone, Oregon Formation, and Camp Nelson Limestone.

All of the area studied to date has been in the lower portion of the Clays Ferry Formation and the upper two-thirds of the Lexington Limestone. The lower third of the Lexington Limestone (including the Logana and Cridersville members) and the three formations below it are exposed only in the gorge of the Kentucky River and the lower reaches of its tributtaries, and underlie areas not yet investigated. Furthermore, it is believed the subsurface circulation of meteoric water within the area studied does not extend into these units. Except for a few comments in Section F9, these lower units will not be considered, therefore.

The principal lithologic characteristic of hydrogeologic interest in the Lexington Limestone and overlying Clays Ferry Formation is the amount of insoluble material in the latter and in units of the former. This factor has been considered a major control in the development of solution openings by most earlier workers (Hamilton, 1948, 1950; Palmquist and Hall, 1961; Mull, 1968; Faust, 1977). Stratigraphic descriptions of the Clays Ferry Formation and the various subunits accompany the published geological quadrangles of the area studied (Allingham, 1972; Black, 1964, 1967; Cressman, 1964, 1967, 1972; Cressman and Hrabar, 1970; Kanizay and Cressman, 1967; MacQuown and Dobrovolney, 1968; Miller, 1967; Pomeroy, 1968, 1970). These are believed to be based generally on hand specimen examination and usually state the approximate percentage of clay, chert, and other insoluble components, as well as noting the occurence of minerals such as dolomite and apatite.

In a study of the Lexington Limestone in Franklin County, Fisher (1968) found that the maximum insoluble content at the Grier and Tanglewood limestone members was 15% and averaged less than 5%. His data also indicate that the maximum content of insoluble minerals in units generally considered argillaceous (Macedonia Bed and Brannon Member) was only 25%, and that lithologies usually described as shales are usually more than 50% calcite and dolomite.

Cressman (1973) calculated normative mineral percentages based on chemical analysis of 15-cm core segments from the Clays Ferry Formation and the Millersburg, Brannon, Tanglewood Limestone, and Grier Limestone members of the Lexington Limestone. Analyses were performed on five core segments selected randomly from the core available for each of the five units. The mean quartz plus clay content calculated for the Grier and Tanglewood limestone members were 8% and 5% respectively. For the remaining three units (considered argillaceous) these amounts were: Brannon Member, 38%; Millersburg Member, 35%; and Clays Ferry Formation, 44%.

Although dolomite is present in most of the units, expecially the more argillacious ones, it generally occurs as isolated rhombs. Fisher found the dolomite-calcite ratio to be generally less than 0.2 and to exceed unity only in one thin (less than 1 m) bed in the Grier Limestone Member. The normative mineralogy of Cressman (1973) yields mean values of this ratio to be 0.1 and 0.17 for the Grier and Tanglewood limestone members, respectively; and to range from 0.23 to 0.46 for the three argillacious units he examined (see above).

The stratigraphic nomenclature used on the various geologic maps is not always consistent, and the terminology of Cressman (1973) will be used in this report. Except for the Clays Ferry Formation and Millersburg Member, all of the argillaceous units (all units of the Lexington Limestone except the Clays Ferry) are less (usually considerably less) than 6 m thick. The delineation of the various units is based on lithology, and the units show complex gradational and intertonguing relationships which often result in multiple occurrences of a unit in the stratigraphic section.

In the northeast Woodford County, Northern Fayette and Southern Scott Counties, and Walnut Hill areas, the relatively pure Tanglewood and Grier limestone members make up most of the section. The argillaceous Millersburg Member, Greendale Lentil and Stamping Ground Member occur within the

Tanglewood, the Brannon and Cane Run members at or near the Tanglewood - Grier contact, and the Macedonia Bed within the underlying Grier. In the Mercer County area, two relatively pure units overlie the Tanglewood, and only two of the argillaceous units are present. These relationships, which are considerably simplified, are shown in Table 1. Subdivisions of the pure limestone units in the Mercer County area (i.e., Cornishville and Salvisa beds) and the thin pure Devils Hollow Member within the Tanglewood in the northeast Woodford County area been omitted.

Limestone Units	Argillaceous Limestone Units
	Clays Ferry Formation
	Millersburg Member**
Sulpher Well Member*	Greendale Lentil**
Perryville Limestone Member*	Stamping Ground Member
Tanglewood Limestone Member	Brannon Member
Grier Limestone Member	Cane Run Member**
	Macedonia Bed

Table 1. Stratigraphic units in the study area. All (except Clays Ferry Formation) are units of the Lexington Limestone. * indicates unit present only in Mercer County area; ** indicates unit not present in Mercer County area.

A3c. Previous Hydrogeologic Investigations

A number of hydrogeologic studies of the Inner Bluegrass Karst Region have been published. The earliest of these was by Matson (1909), which dealt with the larger Bluegrass region, which includes extensive non-karst areas outside the Inner Bluegrass Karst Region. He presented data on a number of wells in the present study area (e.g., 48 in Fayette County, 30 in Scott County, and 20 in Mercer County) but with such general locations that they could not be utilized in this study. His discussions of the hydrogeology are quite general and lack conclusions regarding controls of groundwater occurrence and movement in the Inner Bluegrass Karst Region. Although he mentions a trace to a spring with oil and NaCl, and that NaCl was used in an "examination" of Royal Spring

(Matson, 1909, p. 80-81), he gives no location information. The only published information on water tracing in the region prior to the present study was presented by Jillson (1945), who established flow connections in the Roaring Spring ground water basin (see Section B).

Hamilton (1950) reported an inventory of 964 wells in a four-county area (Bourbon, Fayette, Jessamine, and Scott). Although he lists the total depth of all but a few of these, he could report water levels in only 56 and hence could not prepare a map of the potentiometric surface. He states that only about one out of five wells drilled is productive (Hamilton, 1950, p. 47-48) and concluded (also in Hamilton, 1948) that solution porosity is limited to a depth of about 25 meters, that such porosity is developed mainly along joints and is greatest in topographically low areas. He states that argillaceous limestone units within the Lexington Limestone play a major role in that they severely inhibit the downward circulation of meteroic water and hence retard the development of solution porosity in the rocks that underlie them. His maps which delineate areas of high, intermediate and low probability of obtaining a satisfactory yield and quality of groundwater are apparently based mainly on stratigraphy.

A series of hydrogeologic maps covering the Inner Bluegrass Karst Region (Hall and Palmquist, 1960 a, b, c, d; Palmquist and Hall, 1960 a, b, c) were issued as part of a state-wide project, and a discussion of the hydrogeology of the larger Bluegrass Region (whose area is nearly 30,000 km^2) was published in Palmquist and Hall (1961). The hydrogeologic maps indicate areas of high, intermediate, and low probability of satisfactory well yield and quality. Although this is the same approach used by Hamilton, the two assessments are often quite different for the same area (Hamilton, 1950; Palmquist and Hall, 1960 c). Variations between the assessments are probably due both to differing evaluation criteria and a reflection of the density of well control. Their map (Palmquist and Hall, 1960 c) of the same four counties studied by Hamilton (1950) is apparently based on 64 wells and 31 springs, as opposed to the 964 wells listed by Hamilton. Their summary states that about 35 wells and springs were inventoried in each county and that water levels were measured in most wells (Palmquist and Hall, 1961, p. 3, 15) but they give neither the water level data nor a map of the potentiometric surface.

The summary (Palmquist and Hall, 1961) covers the entire Bluegrass region, and it is difficult to separate their conclusions on the Inner Bluegrass Karst Region from the largely unkarstified areas which surround it. They appear to ascribe differences in well yields in the Inner Bluegrass Karst Region more to topographic position than to stratigraphy (which seems to be reflected in their hydrogeologic maps), which is more or less the reverse of Hamilton's (1950) criteria. They also state that "less than half" of the wells drilled in the bedrock are successful (Palmquist and Hall, 1961, p. 21).

Henderson and Krieger (1964) presented a summary of the geochemistry of waters of the entire Bluegrass Region. A brief report and map on the hydrogeology of Fayette County by Hopkins (1966 a) explains groundwater flow in terms of regional and local potential gradients controlled mainly by topographic factors and evaluates areas along mapped surface streams as having the best prospects for groundwater development.

A report by Mull (1968) also dealt with the hydrogeology of Fayette County, but the most detailed groundwater investigation in the Georgetown quadrangle extended to North Elkhorn Creek in Scott County. He considered that the direction of groundwater movement was controlled by the dip of the rocks and the topography, and presented his data on water levels in 54 wells on a structure contour map. The groundwater of the Georgetown quadrangle is discussed further in Section F4a.

A study of wells in the Centerville Quadrangle in Bourbon, Fayette, and Scott Counties (Johnson, 1970; Johnson and Thrailkill, 1973) was designed to evaluate the relative importance of the various factors proposed by earlier workers. Based on information (much of it from Hamilton, 1950) from 82 wells classified as adequate, sulfur, salt, or dry, nonparametric statistical methods were used to test the effect of a number of topographic, stratigraphic, and structural variables. Although apparently significant relationships were found, the interdependence of topographic and stratigraphic variables in an area of nearly horizontal beds made the results difficult to interpret.

Faust (1977), in a study of a six-county area (Bourbon, Clark, Fayette, Jessamine, Scott, and Woodford), prepared the first potentiometric map in the region. At the small scale of the map, it appears to conform rather closely to topography. It was based on data from more than 500 wells (Faust, 1977, p. 9) but the data are not shown. He also outlined the recharge areas of a number of springs and wells, including Royal Spring, Spring Station Spring, and Versailles Spring. Like earlier workers, he believes the yield of wells is related both to topography and stratigraphy.

There are also a number of statewide reports which furnish specific hydrogeological information within the region. These include Van Convering (1962) on large springs, Hopkins (1966 b) on the elevation of the fresh-saline water interface, Whitesides (1971) on specific capacities of wells, and a series of annual water resources reports containing daily water level data in (currently) four wells in the Inner Bluegrass Karst Region (U.S. Geological Survey, 1981, is the most recent).

Other publications dealing primarily with other aspects of the geology of the region have included data and discussions of the hydrogeology. MacQuown (1967) located 16 springs and 2 wells in a study of the Curdsville Limestone Member, the basal unit of the Lexington Limestone. He found that some of the springs emerged at or near the contact of limestone beds and thin bentonites and other shale units, and that the vertical intergranular porosity and permeability of the Curdsville was quite low. Another aspect of his investigation showed that trends of sinkhole and stream allignments were similar to joint orientations in the Bryantsville quadrangle in the southern part of the region. An expanded discussion of this relationship can be found in Hine (1970), who also showed joints and fracture traces (identified by soil tone on aerial photographs) tended to be parallel as well, and who located 5 wells in the Bryantsville quadrangle, at least one of which was on sinkhole trend.

Portions of the work described in the present report have already appeared (McCann, 1978; Thrailkill and Troester, 1978; Thrailkill, 1980; Thrailkill, et. al., 1980; Spangler and Thrailkill, 1981; Thrailkill, et. al., 1981, Spangler, 1982) or has been accepted for publication (Thrailkill, et. al., accepted for publication).

A4. Methods

The results of dye traces and observations of the discharge of major springs were the principal organized data collected during the study. Large amounts of time had to be expended in field reconnaissance prior to obtaining these data, and a major activity was also maintenance of a computer data file to record it and allow it to be retrieved. More-or-less standard methods, which will not be described, were used for the variety of supporting activities (such as mapping some of the larger caves).

A4a. Field Reconnaissance

The primary objective of field reconnaissance was to locate the major springs in an area in order to monitor them with dye detectors continuously while dye introductions were made in the area. Despite the availability of large scale (1:24000) topographic and geologic maps and published hydrogeologic maps and reports, most of the major springs were located only by interviews with landowners and local residents, including some of the larger third magnitude springs (see Section A4c and Table 2) such as Big, Vaughans, and Slacks Springs as well as most of the smaller ones.

The second objective of the field reconnaissance was to locate swallets, discrete openings where surface drainage is diverted underground where dye could be introduced. Although some of these are shown on (or can be easily inferred from)topographic maps, many, including all those along surface streams, had to be discovered in the field. Further, although water enters the subsurface in the bottoms of all sinkholes, in most of the smaller sinkholes it is water that infiltrates the soil and there is no open swallet. Considerable effort was expended in finding a swallet (in a sinkhole or elsewhere) in critical areas, and in waiting for surface runoff in order to introduce dye. In three cases, dye introductions were made with water (about 3800 l) from a tank truck.

A4b. Dyes and Detectors

The dye tracing techniques used by J. F. Quinlan (Quinlan and Rowe, 1977; Quinlan, 1977; Quinlan and Ewers, 1981) in the karst area near Mammoth Cave, Kentucky were initially adopted for the present study. Except for changing the design and material used for the cotton detector, only minor modifications were made in these techniques during the study.

Of the 121 original dye introductions made (Appendix 1) 70 were of optical brightener. This dye, which is a common additive to laundry detergents, is selective for adsorption on cotton, and will show a visible bluish fluorescence on fabric that has been immersed in concentrations as low as 17 parts per billion for 24 hours at a temperature of 27°C (Byrd, 1981; Thrailkill, et. al., in preparation). This value is for a formulation designated (Society of Dyers and Colourists, 1971) as Generic Name Fluorescent Brightener 28 (Constitution Number 40622) used for all of the brigntener tracers. It was selected because of its demonstrated lack of toxicity and other characteristics (Quinlan and Rowe, 1977). Three different lots were used, with the particular lot identified by number (Appendix 1). Further information on its behaviour will be found in Byrd (1981) and Thrailkill, et. al. (in preparation).

Direct yellow dye was used in 40 of the remaining 51 original dye introductions, either because one or more of the possible detection points showed an optical brightner background (presumably derived from laundry detergents in sewage or septic tank effluent), or to avoid confusion with an optical brightener trace being conducted at the same time. This dye, G. N. Direct Yellow 96, Constitution Number unassigned (Society of Dyers and Colourists, 1971) was also selected for its characteristics (including absence of toxicity) by Quinlan (1977). It is also highly absorbed on cotton and a concentration of 17 ppb produces a distinct yellow fluorescence on fabrics after 24 hours of immersion at 22°C (Byrd, 1981; Thrailkill, et. al., in preparation; also see for further information). Six different lots from several suppliers were used.

Fluorescein was used for all but one of the remaining 11 original dye introductions, mainly to allow an additional trace to be undertaken at the same time traces were underway using other dyes. This widely-used dye is adsorbed by a charcoal detector. Dye from a single purchase was used for nine of the traces, and a single unsuccessful dye introduction (B1, Appendix 1) was made with fluorescein from an unknown source. Fluorescein is G. N. Acid Yellow 73, C. N. 45350 (Society of Dyers and Colourists, 1971). The final trace was conducted with acid red dye (G. N. Acid Red 52, C. N. 45100, Society of Dyers and Colourists, 1971) detected by adsorption on charcoal (McCann, 1978).

Detectors consisting of a pad of surgical cotton (Quinlan, 1972; Quinlan and Ewers, 1981) were used in the early phase of the study for optical brightener and direct yellow traces. In order to permit evaluation by a spectrofluorometer, a detector utilizing woven cotton fabric was designed and used for all traces performed after January 1, 1978. The fabric detector (described in Byrd, 1981, and Thrailkill, et. al., in preparation) was found to be as effective as the surgical cotton detector for visual examination and was less sensitive to contamination. The design of the charcoal detectors (basically a small cylinder of nylon screening filled with charcoal) is described in Spangler (1982) and Thrailkill, et. al. (in preparation).

Detectors were usually supported in the water with a "gumdrop" (Quinlan, 1977; Quinlan and Rowe, 1981), which consists of a wire arm embedded in a concrete base. Quinlan's design was slightly modified by embedding two or more wires to provide both added strength and additional arms to support multiple detectors. Where the water depth was insufficient (less than about 20 cm) to submerge a detector attached to a gumdrop, the detector was attached to a "hairpin", a doubled length of galvanized wire whose free ends are thrust into the stream-bottom sediment. The detector, which is on a wire frame, is supported vertically in the water flow by the hairpin and attached to a loop at its top.

In the laboratory, fabric detectors were rinsed under a vigorous flow of water and allowed to air dry in the dark. Evaluation was by examination under a hand-held ultraviolet lamp at both 254 and 366 nm. Facilities for instrumental evaluation of fabric detectors became operational near the end of the study, and a few critical traces were evaluated using the spectrofluorometer. Charcoal detectors were elutriated with an alcohol solution which was examined either visually or instrumentally. Additional information on detector evaluation will be found in Byrd (1981), Spangler (1982), and Thrailkill, et. al. (in preparation).

A4c. Discharge Observations and Spring Magnitude Determination

Discharges were estimated at the time of each visit to springs, swallets, and other flows of water. Various methods were used, from a simple inspection for flows of one or two liters per minute to establishment of a rating curve based on temporary stage indicators and a series of discharge determinations using a flow meter (Price Pygmy Meter) at some of the larger springs. By far the most common method used was to measure or estimate the cross-sectional area at a point in the channel and average velocities from floating bubbles, leaves, or other objects.

No claim of high precision is therefore made for the discharge data obtained. Comparisons between determinations made at the same time by two or more individuals suggests that the precision (95% confidence interval) is between -50% and +100%, i.e., the actual flow for an estimated value of 10 l/s is between 5 and 20 l/s 19 times out of 20. It is also possible that the accuracy of estimates by an individual may be generally too high or too low, although efforts were made to detect and correct such a systematic bias.

Where seven or more discharge observations were available for a spring, they were used to estimate its size by grouping the observations into one-half order-of-magnitude classes (e.g., 30-100 l/s, 100-300 l/s). The range of each class is approximately the same as the 95% confidence interval of the discharge estimates. These limits correspond approximately with those used for larger springs in a classification proposed by Meinzer (1927). He considered first, second, and third magnitude springs to be those flowing more than 100 cubic feet per second (2830 l/s),10(283 l/s) to 100 cfs, and 1 (28.3 l/s) to 10 cts, respectively. The intermediate limits (e.g., 100 l/s) used here approximate the geometric mean of the Meinzer classes and divide his magnitudes into what will be termed, for example, a smaller (30-100 l/s) and larger (100-300 l/s) third magnitude. Spring magnitudes were assigned by the class which included the median, as indicated in Appendix 4. The magnitude designation was extended to smaller springs using the same (logarithmic) intervals, departing from the Meinzer classification of such springs which was based on a shift in units to gallons per minute.

Discharge estimates were made in units of gallons per minute or cubic feet per second (because the use of more familiar units tended to promote accuracy) and hence none fell exactly on class limits when converted to liters per second. When the median fell on a class limit (equal number of observations in larger and smaller classes), the spring was assigned to the smaller class. Extended periods of low discharge were avoided for water tracing, hence there were fewer discharge observations made during such periods. The bias toward a higher median spring discharge this would create may be at least partly offset by the rapid rise and decline in spring discharge that occurs following heavy rainfalls. Thus few such high flows, which are volumetrically important to the total annual discharge, were observed and recorded. Because the region's major springs do show large variations in discharge, however (typically two or more orders of magnitude, Appendix 4), the assignments of magnitudes (Table 2) should be considered approximate, especially for springs with fewer than 20 or so discharge observations.

A4d. Data Management

Because of the volume of data generated during the study, including site locations, dye trace results, and discharges, a computer data file was established. This file currently contains more than 8000 card images stored on disks and tapes. Programs were also written to produce summaries and to construct computer drafted maps (Thrailkill, et. al., in preparation).

	Spring		Groundwater Basin		Report	
	Name	Magnitude	Name	Area(km^2)	Fig.	Section
1.	Bailey Spring	-	-	-	4	D1b
2.	Baker Cave Spring	4+	same	2	3	C1h
3.	Big Spring	3+	same	9	3	C1a
4.	Blue Spring	-	same	1	2	D1k
5.	Boggs Spring	4-	same	1	4(I)	E1a
6.	Boone Spring	4-	Distillery Sp.	<.5	3	C1c
7.	Bryan Station Sp.	-	-	-	4	D1b
8.	Burgin Spring	3-	same	11	3	C1b
9.	Cougar Spring	5+	-	-	2	B1a
10.	Cornett Spring	4-	same	1	4	D1j
11.	Cove Spring	4+	same	1	3	C1g
12.	Distillery Spring	-	same	2	3	C1c
13.	Elkhorn Spring	-	same	<.5	4	D1j
14.	Eureka Spring	3-	same	2	3	C1i
15.	Gano Spring	3-	same	2	2,4	D1g

	Spring		Groundwater Basin		Report	
	Name	Magnitude	Name	Area(km^2)	Fig.	Section
16.	Gay Sink Spring	3-	Roaring Sp.	7	2	Bla
17.	Hartman Spring	3-	same	1	3	Cle
18.	Holland Spring	-	same	<.5	4	Dli
19.	Humane Spring	3-	same	1	3	Cli
20.	I-75 Pond Spring	-	same	<.5	4(I)	Elb
21.	Jennings Spring	-	same	1	4	Dlk
22.	Lindsay Spring	3+	same	5	4	Dld
23.	McGee Sink	-	Vaughan Sp.	4	4	Dlc
24.	Nance Spring	-	same	3	2	Dlh
25.	Paxton Spring	-	-	-	4	Dlc
26.	Pin Oak Spring	4-	same	2	2	Blb
27.	Railroad Spring	-	same	2	3	Cli
28.	Roaring Spring	3+	same	12	2	Bla
29.	Royal Spring	2-	same	15	4	Dla
30.	Russell Cave Spring	3+	same	9	4	Dlb
31.	Santen Spring	4+	same	2	4	Dlj
32.	Shawn. Copper. Sp.	4+	same	1	3	Clf
33.	Shawn. Hefer Spring	3-	-	-	3	Clf
34.	Shawnee Run Spring	3-	same	4	3	Cld
35.	Silver Springs	3-	same	7	4	Dle
36.	Slacks Spring	3-	same	15	2,4	Dlf
37.	Slacks Cave	-	Slacks Sp.	13	2,4	Dlf
38.	Sloans Spring	4-	Slacks Sp.	12	2,4	Dlf
39.	Spring Lake Spring	3-	same	1	4	Did
40.	Spring Station Sp.	3-	Royal Spring	10	2	Bla

	Spring		Groundwater Basin		Report	
	Name	Magnitude	Name	Area(km^2)	Fig.	Section
41.	Steeles Spring	-	same	1	2,4	D1k
42.	Swopes Spring	-	Roaring Spring	-	2	B1a
43.	Tevis Spring	5-	same	1	4	D1i
44.	Spring 13	4-	same	2	2	B1b
45.	Spring 13B	4-	-	-	2	B1b
46.	Vaughans Spring	3+	same	5	4	D1c
47.	Versailles Spring	4+	same	2	2	B1b
48.	Votah Spring	3-	same	3	3	C1i
49.	Wests Spring	3-	-	-	2	B1a
B3	-	-	Sharp Swallet	1	4	D1i
C16	-	-	Duval Cave	1	3	C1i
D57	-	-	Ansley Swallet	1	2	D1j

Table 2. Springs and groundwater basins in the study area.

B. NORTHEAST WOODFORD COUNTY

M. R. McCann and J. Thrailkill

This was the first area investigated as part of the Inner Bluegrass Karst project, and was selected for two principal reasons. First, it was necessary to investigate the suitability for the Inner Bluegrass Karst Region of dye tracing techniques used in the Mammoth Cave area (Quinlan and Rowe, 1977). Because the only previous water tracing for which results were available (Jillson, 1945) had been performed in this area, its selection allowed these techniques to be evaluated by conducting the initial traces where flow connections had already been established. Second, there was considerable local interest in the effect suburban development in the Versailles area might have on groundwater in the northern part of Woodford County.

B1. Groundwater Basins

Four groundwater basins were identified and at least partly delineated by 12 dye introductions, all of which resulted in traces, of which three were duplicates and one was a surface trace. Seven of the dye introductions were original and 5 were downstream segments of serial traces. A potentiometric surface map was prepared, and various other information is available in McCann (1978).

Groundwater basins are named for the spring which drains them, and other springs may be within or discussed with a basin. An underlined number following the name of a basin or spring identifies the spring and basin on Figure 2 and in Table 2. Underlined letters and numerals used to describe a dye input point or dye trace are the dye introduction numbers (Appendix 1) for the first successful trace from a dye input point, and are used to lable such points on Figure 2.

B1a. Roaring Spring Basin (28)

Roaring Spring (28) is a larger third magnitude spring and is the largest in the area. It rises from a number of outlets over a distance of about 100 m along the south bank of South Elkhorn Creek. During high discharges flow emerges from as many as 12 outlets, including a cave 5 meters above the elevation of the creek and lower outlets, but during low flow only 3 or 4 outlets are active.

Dye traces were made to Roaring Spring from three swallets, the most distant (Big Sink, Ala) more than 13 km to the southwest. Before reaching Roaring Spring, flow from these swallets emerges in two karst windows, first at Gay Sink Spring (16) and then at Spring Station Spring (40). Karst windows are deep sinkholes (or elongate depressions) in which major subsurface flow appears at the surface. The flow from these springs (both of which are smaller third magnitude) disappears in a swallet a few hundred meters below the spring. Springs feeding sinking streams in sinkholes well above the level of major subsurface flow, such as Swopes Spring (42) do not represent karst windows.

The boundaries of the Roaring Spring basin are reasonably well defined only to the southwest, where tracing defined three small adjacent basins(discussed below). Its boundaries to the east are unknown, and much of the area between Big Sink (Ala) and South Elkhorn Creek may lie within it. During most of the Roaring Spring basin traces, detectors were maintained in Cogar Spring (9) and Wests Spring (49) but no traces were detected. Cogar Spring is quite small (larger fifth magnitude) and probably has a very limited groundwater basin, while the basin of the larger Wests Spring probably lies east of it. The basin as outlined has an area of 12 km^2.

B1b. Other Basins: Spring 13 (44), Pin Oak Spring (26), Versailles Spring (47)

Three small groundwater basins were each defined by a single trace, suggesting an area of about 2 km^2 for each. Spring 13 (44) is a smaller fourth magnitude spring, and is close to another spring of about the same size (Spring 13B, 45) in which no traces were detected. Pin Oak Spring (26) is also of this size, and its basin underlies an area north of the city of Versailles. The basin of Versailles Spring (47) probably underlies much of Versailles.

B2. Discussion

The scope of this study, the first in the Inner Bluegrass Karst Region, was limited by the necessity of developing and testing suitable dye tracing techniques, as well as the lack of any background knowledge on the nature of subsurface flow in the region. The results of the dye tracing and observations made during the investigation provided enough information on the hydrogeologic system to begin to evaluate explanations that had previously been offered by others, and which would be further examined in later studies.

B2a. Nature of Groundwater Basins

All of the dye introductions made in the Roaring Spring basin are believed to be in swallets previously traced by Jillson (1945), and the pattern of subsurface flow found generally agrees with the one he presented. The one exception seems to be that there is no evidence that the flow from Big Sink (A1a) passes beneath swallet A3a as he showed (Jillson,1945, p. 8), since the flow does not appear at the surface at this point.

There appears to be no accordance between the general direction of subsurface flow in the Roaring Spring basin and present or former surface drainage basins. What appears to be two pre-existing lines of surface drainage trend approximately north across the basin. The easternmost of these extends from near the intersection of the Bluegrass Parkway and US 60 through swallets A1a and A3a to Midway and joins South Elkhorn Creek (Fig. 2). North of Wests Spring there is normal surface drainage, but to the south it is a paleovalley with no surface channel, or consists of short segments of surface flow which terminate in swallets such as Big Sink (A1a) and A3a. Such karst landforms are termed blind valleys, but the entire preexisting drainage is here referred to as the Lees Branch paleovalley. A similar drainage line lies about 5 km to the west (Beals Run paleovalley). The Spring Station Spring (13) karst window occupies the middle of its course, its northern part contains a surface stream, and its southern part is a paleovalley. The Pin Oak Spring basin also crosses a major surface divide.

It was also found that much of the subsurface water flow in the area is at rather shallow depths and emerges at small, high level springs. Such shallow flow is occurring in close proximity to deeper flow conduits, as evidenced by Swopes Spring, which feeds a stream that enters a swallet and joins the deeper flow system.

B2b. Effect on Northern Woodford County Groundwater From Versailles Area Development

Based on the dye traces performed, it appears that deep subsurface flow on the northern outskirts of the city of Versailles is to Pin Oak Spring (26), and that to the east, as well as surface flow into Big Sink (A1a) will eventually emerge at Roaring Spring (28) after passing through Gay Sink Spring (16) and Spring Station Spring (40). There is no evidence, however, that any of the flow from Big Sink (A1a), or any other in the Roaring Spring basin, enters lower Lees Branch or is present in the surbsurface anywhere near the town of Midway. The understanding of the nature of subsurface flow that has been gained by other studies in the region (and discussed in Section F) suggests that such flow out of a major basin is highly unlikely.

B2c. Factors Influencing Subsurface Flow and Groundwater Basins

There are numerous sinkholes in the area, and some are aligned in linear trends. One such trend extends west from Big Sink (A1a) to dye introduction point A5. The two ends of the trend are in different groundwater basins, however, and flow does not occur along its length. To the north, dye introduction points A3a and A7a are on a northwest tending alignment, and flow from both points is to Gay Sink Spring (16). The spring, however, lies off the trend to the southwest. On a larger scale, it will be noted that the overall trend of the Roaring Spring basin from Big Sink (A1a) through Gay Sink Spring (16)and Spring Station Spring (40) to Roaring Spring (28)is approximately linear.

The relationship of subsurface flow direction to the dip of the rocks is equally ambiguious. The dip is shown by structure contours at an interval of 3.0 m on the geologic maps of the area (Black, 1964; Cressman, 1964; Pomeroy, 1968, 1970). Although the general flow direction in the

Roaring Spring basin (28) is down the regional dip to the northwest, near the center of the basin it must flow at least 10 m updip after crossing a local structural low. In the Spring 13 basin (44), on the other hand, flow is to the south, approximately down the local dip but a large angle to the regional dip.

There is little indication that major subsurface flow is unable to penetrate either mapped argillaceous units or unmapped shales. One of the eight dye introductions was made within the outcrop area of the argillaceous Brannon Member and two were above this unit. All of the major springs, including those to which these three dye introductions were traced, are in the underlying Grier Limestone Member, indicating penetration of the Brannon beneath the surface. Also, an inspection of the geologic maps of the area shows that numerous sinkholes penetrate the Brannon, indicating its inability to inhibit the subsurface flow responsible for the development of the sinkholes.

There is likewise little evidence that the major subsurface flow conduits are perched on argillaceous units. All eight of the major springs located in the area emerge at various points within the upper 8 m of the Grier Limestone Member. The lower outlets of Roaring Spring (28) and Wests Spring (49) are near the stratigraphic position of the argillaceous Macedonia Bed, which is mapped along South Elkhorn Creek about 7 m below the top of the Grier. The stratigraphic position of the other major springs (including the higher outlets of Roaring Spring), four of which emerge 5 m or less below the top of the Grier, cannot be explained by perching on the Macedonia Bed, however.

In contrast, there is some indication that the smaller high-level springs may often be perched on argillaceous beds. Swopes Spring emerges at about the stratigraphic position of the Brannon Member, although this unit is very thin or absent at the location of the spring.

C. MERCER COUNTY AREA

W. M. Hopper, Jr., and J. Thrailkill

This area was selected for study primarily because it was some distance away from the Northeast Woodford County area study, which had recently been completed, and the Northern Fayette and Southern Scott Counties area study which had just begun. Because of this geographic separation, it was felt that hydrogeologic characteristic common to all the area would probably be found in other areas of the Inner Bluegrass Karst Region as well. In addition, the somewhat different stratigraphy and structure of the area would assist in the evaluation of the importance of these factors to subsurface flow.

C1. Groundwater Basins

Twenty-five dye introductions resulted in the identification of 13 groundwater basins. One of the dye introductions was the down stream segment of a serial trace, three were not detected, and one was for a duplicate trace. In the following discussion, an underlined designation following the name of a spring, groundwater basin, or used for a dye introduction point or trace identifies the feature on Fig. 3 and in Table 2 (see Section B1 for more information).

C1a. Big Spring Basin (3)

Big Spring (3) in the city of Harrodsburg is a large third magnitude spring, and is the largest in the area. Its flow emerges from a rise pool and follows a channel a few meters long to Town Creek, a tributary of the Salt River. Two fluorescein traces were made to Big Spring in 1973 by the Mercer County Health Department (G. Van Sant, personal communication, 1978) from the southeast (X1, HRDB SC 0.55 1.17, see Section A2 for an explanation of location designation) and northeast (X2, HRDB SC 1.39 4.23), and three additional traces were made during the present study also from the southeast and northeast. The most distant of these (C19) appeared in a flow encountered in a quarry which feeds a swallet (C9) previously traced to Big Spring.

The lower portions of the basin underlie the Town Creek surface drainage basin, but the margins of the basin extend into adjacent surface basins. To the southeast, C19 is in a sinkhole in the headwaters of a surface drainage which roughly parallels Town Branch. To the northeast, C7 is east of the surface divide between the Salt and Kentucky Rivers in the Sinkhole Plain paleovalley (See Section C1b).

Inspection of the geologic maps of the area (Allingham, 1972; Cressman, 1972)shows the major subsurface flow is down the regional dip to the west, although the trace from C19 is more nearly along strike and that from C7 must cross a 5 m structural high at the Salt-Kentucky River surface divide.

Over 1200 m of one of the major flow conduits could be examined underground at X2. Overall, the conduit is nearly straight and follows a line between C7 and Big Spring. It is occupied throughout its length by a stream (which is probably carrying the flow from C7), and the conduit, whose height and width vary between 1 and 3 m, meanders with a half wave length of about 20 m. The ceiling is usually flat and the entire conduit appears to be very nearly parallel to bedding.

A number of short faults, fluorite-barite veins, and vertical joint sets are shown on the geologic map within the basin. Their predominant orientation is north-south and east-west, with a few northwest-southeast, parallel to the apparent flow lines to Big Spring from the southeast. The northeast-southwest trend of the conduit described above is not represnted.

C1b. Burgin Spring Basin (8)

Burgin Spring (8) flows from three outlets within about 50 m of each other in the town of Burgin. The flow drains to the Kentucky River via Lake Herrington (Dix River). Traces were made to the spring from three widely separated input points to the west indicate a basin area of about 11 km^2 for this smaller third magnitude spring. Thus the indicated area of its basin is larger than the 9 km^2 estimated for the Big Spring basin, but the spring is smaller than Big Spring (larger third magnitude).

The single trace from the southwest (C14) was from a large sinkhole 2 km long and up to 1 km wide located on the Salt-Kentucky surface divide, and the dye introduction point is only 1 km distant from C19 in the Big Spring basin (3). The northernmost trace (C4) was from the southern margin of what was termed the sinkhole plain paleovalley during the study. This is a low-relief area of about 30 km^2 which now has no surface drainage but at one time appears to have been drained by a tributary of Shaker Creek. Five dye introductions were made from swallets within the paleovalley (C4, C7, C15, C20, and C24), which resulted in traces to four different springs, none of which are within the paleovalley.

Unlike the Big Spring basin (3), flow in the Burgin Spring basin is updip, with all three dye introduction points being structurally lower than the spring. The longer traces (C4 and C14) were from swallets in the Tanglewood Limestone Member, and their flow to Burgin Spring, which is 20 meters below the top of the underlying Grier Limestone Member, must penetrate about 30 m of section, including the argillaceous Macedonia Bed. The predominant trend of mapped joints, faults, and veins within the basin is north-south, and hence at a high angle to the line of traces.

Clc. Distillery Spring Basin (12)

A spring on the property of an inactive distillery about 1 km northeast of Burgin drains a groundwater basin of about 2 km^2. Although small, the basin is of interest because the initial dye introduction (C6a) is in the upper end of a second paleovalley (east of the Sinkhole Plain paleovalley) of Shaker Creek, which flows to the Kentucky River. Subsurface flow in the basin to Distillery Spring (12) thus crosses the former surface divide between the Dix River, into which the spring drains, and the Kentucky River. The flow from C6a appears at Boone Spring (6) in a karst window enroute to Distillery Spring. Permission to visit Distillery Spring could not be obtained and no discharge observations were made (traces were detected in the stream fed by the spring which may receive surface drainage as well).

Subsurface flow in the basin is generally downdip into a small structural depression at Distillery Spring. The swallet (C6a) is fed by a high-level spring apparently perched on the Macedonia Bed and all of the traced subsurface flow is in the Grier Limestone Member beneath this unit.

C1d. Shawnee Run Spring Basin (34)

Shawnee Run Spring (34), which is named on the Harrodsburg quadrangle, is on Shaker Creek, not Shawnee Run. It flows from the Grier Limestone Member about 2 m above its base and is thus stratigraphically lower than any other spring at which traces have been detected in the Inner Bluegrass Karst Region to date. Two of the three traces (C15 and C20) are from swallets in the Sinkhole Plain paleovalley (Section C1b) and the third swallet (C5) is in the eastern paleovalley discussed in the previous section, about 1 km north of C6a which drains to Distillery Spring (12). All three swallets in the Shawnee Run Spring basin are just below the outcrop of the Macedonia Bed and are fed by high-level springs perched on this unit.

Flow directions from the more distant swallets (C15 and C20) are updip, and approximately parallel to a short (400 m) fault mapped between the swallets and the spring, which emerges at the trace of a similar short fault trending at right angles to the first. Each fault has about 3 m of stratigraphic displacement.

C1e. Hartman Spring Basin (17)

A small basin to the northwest of the Shawnee Run Spring basin was indicated by a single trace to Hartman Spring (17) from a swallet (C24) in the Sinkhole Plain paleovalley (see section C1b). Both the swallet and the spring are in the Grier Limestone Member below the stratigraphic position of the Macedonia Bed, which is not mapped in the basin. The direction of flow is updip and at a large angle to the north and northwest trending joint sets mapped at the swallet, which is drained by a conduit with a cross-sectioned area of about 2 m^2.

C1f. Shawnee Copperhead Spring Basin (32)

Two springs are located near the headwaters of Shawnee Run and are labeled on the topographic map as Shawnee Springs. The northernmost of these, here termed Shawnee Copperhead Spring (32), emerges from the Grier Limestone Member about 3 m below the Macedonia Bed. It is on the north side of a fault which is in line with the fault at Shawnee Run Spring

Spring (34) on Shaker Creek (section Cld). A single trace to the spring was made from the downstream end of a cave (C10) in the groundwater basin. At this point the stream in the cave intersects, and may follow, an unmapped northeast-trending fault which may intersect the southeast-trending fault discussed above.

This cave is the longest (2.34 km) investigated in the Mercer County area. It consists of an entrance passage over 1 km long which intersects a main passage near its downstream end at C10. The entrance passage contains a small stream draining sinkholes in the Tanglewood Limestone Member and passes beneath a ridge capped by the Clays Ferry Formation. There is a pronounced change in the cross-sectional shape of the passage as it is followed downstream, which is typically 3 m high and 3 m wide in the Tanglewood, to a narrow canyon 5 m or more high and less than 1 m wide in the underlying Grier Limestone Member. The passage cuts through the Macedonia Bed but its position is not strongly reflected in the passage morphology.

The upstream portions of the main passage is developed along the Tanglewood Grier contact, and a barite-fluorite vein (not shown on the geologic map) is exposed where it is intersected by the passage at a low angle. The downstream portion of the main passage is in the Grier, and intersects a fault as stated earlier.

The other spring in the Shawnee Run headwaters emerges in the opposite side of the valley about 300 m south of Shawnee Copperhead Spring (32). Termed Shawnee Hefer Spring (33) during the study, it flows from a number of outlets over a distance of 60 m along the outcrop of the argillaceous Macedonia Bed. This is the largest spring (smaller third magnitude) in the areas studied in the Inner Bluegrass Karst Region which is clearly perched on an argillaceous stratigraphic unit. No traces were performed to this spring and the limits of its groundwater basin are unknown.

Clg. Cove Spring Basin (11)

Cove Spring (11) flows from a conduit with an average cross-sectional area of 4 m^2, and from two other outlets within 300 m. Although only a single trace was made of the spring it indicated a number of interesting attributes of the basin. The swallet (C22) is in a surface drainage parallel to the one in which the spring is located, and two other swallets are aligned between C22 and the springs. Swallet C22 extends vertically through the argillaceous Brannon Member to the top of the underlying Perryville Limestone Member, and since the spring outlets are at the base of Perryville, the subsurface flow, which is updip, is probably entirely within this unit above the underlying Tanglewood Limestone Member. Between swallet C22 and Cove Spring the subsurface flow must pass beneath a ridge capped with at least 7 m of Clays Ferry Formation.

C1h. Baker Cave Spring Basin (2)

A groundwater basin discharging at Baker Cave Spring (2) was investigated with two dye traces. The basin appears to approximately coincide with the surface drainage basin of what is shown on the topographic map as a perennial stream draining west to the Salt River. In actuality, there is no surface drainage in the valley under normal runoff conditions, which is instead drained by a subsurface conduit beneath the slope of the ridge which bounds it on the south. Two segments of this conduit are accessible, downstream it has a cross-sectional area of about 10 m^2 and upstream (from which trace C3 was conducted) its cross-sectional area is about 3 m^2. The accessible segments are in the Perryville Limestone Member and are overlain by the Brannon and Sulfur Well members and the Clays Ferry Formation which caps the ridge.

The second trace (C8) was from a swallet in a sinkhole on the opposite side of the valley. Although this swallet is shown within the mapped outcrop of the Clays Ferry Formation, the swallet was in the top of the Sulfur Well Member and its conduit must penetrate the argillaceous Brannon Member before passing beneath the valley to emerge at the spring. The dip in the basin is to the southwest, which may account for the location of the conduit to the south of the surface valley.

C1i. Other Basins: Votah Spring (48), Humane Spring (19), Eureka Spring (14), Duvall Cave (C16), Railroad Spring (27)

Three groundwater basins in the Salt River drainage were each indicated by a single trace. Each of these is drained by a smaller third magnitude spring, and each appears to largely underlie a surface valley. From north to south these are the Votah Spring basin (48), the Humane Spring basin (19), and the Eureka Spring basin (14). Flow in each of these is generally downdip to the west. Much of the catchment area of these springs is in urbanized areas in and near the city of Harrodsburg, and Humane Spring (19) showed a very high background of optical brightner.

The final two basins identified (again by single trace only) drain into Mocks Branch, a tributary of the Dix River (Herrington Lake). The most easterly of these was indicated by a trace from Duvall Cave (C16) to a detection point on a stream to the south, but the spring was not located. The Railroad Spring basin (27) lies to the west. Flow in both basins is slightly updip and not obviously related to any mapped structural feature.

C2. Discussion

Observations made during the Mercer County area study generally confirmed and expanded the general results of the Northeast Woodford County area study, and also suggested additional relationships.

C2a. Nature of Groundwater Basins

Additional insight into the relationship between groundwater basins and surface drainage basins was gained as a result of this study. Water traces in six of the thirteen groundwater basins identified were consistent with the groundwater basin underlying a surface watershed. In five of these, however, only a single trace was conducted, and additional tracing may well extend the boundaries of the groundwater basin. The lack of accordance of groundwater basins to paleovalleys seen in the Northeast Woodford County area (section B2a) is even more pronounced in the Sinkhole Plain paleovalley, in that swallets within the paleovalley are located in four different groundwater basins, indicating that present subsurface flow directions, at least in this case, show no tendency to be inherited from former surface flow directions. Finally, the extension of the Big Spring basin (3) into the area east of the Salt River-Kentucky River divide and the lack of accordance with surface watersheds shown in the Cove Spring basin (11) are examples of the lack of correlation bwtween subsurface flow and present surface watersheds.

Because of the number and rather uniform spacing of dye input points in the central portion of the area, it was felt the boundary between the

Big Spring (3) and Burgin Spring (8) basins was outlined with as much confidence in its location as any boundary between basins to date. The indicated area of the Big Spring basin is slightly smaller than that of the Burgin Spring Basin, while the median discharge of Big Spring is larger than Burgin Spring. Given the distribution of dye input points, it is difficult to extend the smooth outline of the Big Spring basin (or to contract that of the Burgin Spring basin), and it may be that undetected fingerlike extensions of the Big Spring basin extend well into the Burgin Spring basin.

C2b. Influence of Structural Factors

The Mercer County area is on the west flank of the Cincinnati Arch, and regional dip is to the west at about 5 m/km with only minor local folding (Allingham, 1972; Cressman, 1972). Westward flow to the five springs in the Salt River watershed is thus down the regional dip, and the gradient between dye input points (Appendix 1) and the springs is often about equal to the amount of dip. Flow in the other eight basins, which are in the Kentucky River watershed (in some cases via Lake Herrington and the Dix River) is more often updip than downdip with similar gradients. A notable example is the Burgin Spring basin (8) in which the flow is almost directly updip. There therefore appears to be no consistent or useful correlation between the direction of subsurface flow as shown by dye tracing and the dip of the rocks.

The predominate direction of mapped joints, faults, and barite-fluorite veins in the area is north-south, with east-west and northwest-southeast trends only slightly less common. Although only the overall direction of flow from dye introduction points to spring is obtained from a dye trace, an inspection of such directions does not suggest that only particular trends (including the above structural directions) are favored. A few of the accessible flow conduits examined underground are relatively straight (and others are not), but joint control, if present in the straight conduits, is not obvious. The best example of such a straight conduit is in the Big Spring basin (section C1a), but its southwest trend would not be predicted from the mapped structural directions. In a cave in the northern part of the area (C1f), the conduit crosses a barite-fluorite vein at a low angle and is apparently uncontrolled by its presence. Two (32 and 34) of the twelve major springs in the area are on the downthrown (and downstream) side of small northwest-trending faults, and the flow to Shawnee Copperhead Spring (32) may follow faults. Overall, however, the presence or trend of faults appears to exhibit little control over subsurface flow.

In the Cove Spring basin (11), the single trace conducted from C22 appears to follow aligned sinkholes which cross the headwaters of a surface watershed adjacent to the one in which the spring is located, and it seems likely that the subsurface flow may be following some structural lineation. Furthermore, the main conduit in the Baker Cave Spring basin (2) to the west, which is indicated by a line between C3 and the spring (2), is fairly straight and is approximately on the same line, and may be controlled by the same feature. If present, it lacks surface expression in the Clays Ferry Formation which crops out between the two basins.

C2c. Influence of Lithology

As discussed earlier (section A2), the overall boundaries of the Inner Bluegrass Karst Region are generally determined by the updip edge of the Clays Ferry Formation. One of the reasons the Mercer County area was selected for study was to investigate the nature of an area near such a boundary, and to test the hypothesis that the degree of development of groundwater basins was related to the time that had elapsed since the Lexington Limestone had lost its Clays Ferry cover by erosion, which would be less near the boundary.

Numerous small sinkholes are shown on the geologic maps of the area in the lower 10 m of the Clays Ferry Formation. Although major karst landforms in the Clays Ferry seem to be absent (swallet C8 within its outcrop area extends into the underlying Sulphur Well Member), the occurrence of sinkholes indicates subsurface conduits are present. In the Baker Cave Spring basin, a conduit with a cross-sectional as large as 10 m^2 lies beneath the outcrop edge of the Clays Ferry (section C1h) and in the Cove Springs basin a smaller conduit passes beneath a ridge capped with at least 7 m of Clays Ferry. Such occurrences did not support the hypothesis of lesser groundwater basin development near the Clays Ferry Formation.

In the Northeast Woodford County area (section B), all of the major springs were in the upper Grier Limestone Member, which suggested the possibility of stratigraphic control of the location of major conduits. In the Mercer County area, however, the major springs emerge from a number of stratigraphic units. In the eastern (updip) portion, most of the springs flow from the middle Grier, below the Macedonia Bed, and one (Shawnee Run Spring, 34) is located only 2 m above its base (see section Cld). In the east, all of the five springs which drain to the Salt River, which flows north about parallel to strike, emerge only slightly above the level of this stream. Consequently, the northernmost spring is stratigraphically lowest (reflecting the lower elevation of the Salt River downstream) and the southernmost spring the stratigraphically highest. Relative to the top of the Tanglewood Limestone Member, from north to south the approximate stratigraphic positions are: Votah Spring (48), 11 m below; Humane Spring (19), 7 m below; Big Spring (3), 5 m below (these three springs are all in the Tanglewood); Eureka Spring (14), at the contact; and Baker Cave Spring (2), 7 m above (in the overlying Perryville Limestone Member). Thus no stratigraphic control of the location of major subsurface flow appears to exist.

There was no evidence from the dye traces conducted that either of the two argillaceous units within the Lexington Limestone in the area influenced major subsurface flow. The Brannon Member crops out on the sides of higher ridges in the western part of the area, and only one dye introduction (C8, see section Clh) was made in a swallet well above its top. Flow from this dye introduction penetrated the Brannon Member underground to emerge at Baker Cave Spring (2) in the underlying Perryville Limestone Member. Two traces in the central portion of the area were made from swallets stratigraphically higher than the Macedonia Bed (e.g., C14, see section Clb), which were detected at springs in the Grier Limestone Member below the Macedonia Bed, indicating its penetration underground.

In contrast, significant untraced subsurface flow appears to be perched on the Macedonia Bed in the central portion of the area. The most striking evidence of this is the smaller third magnitude Shawnee Hefer Spring (see section Clf), but there are also numerous small high-level springs which emerge at the outcrop of the Macedonia Bed in the Sinkhole Plain paleovalley. It appears that much of the infiltrating recharge from areas above the Macedonia Bed is intercepted by it and diverted back to the surface.

As discussed earlier (section Clb), all drainage in the Sinkhole

Plain paleovalley is underground to at least four widely separated springs, and thus the subsurface divides between these four groundwater basins also underlie the paleovalley. The area is not, however, one of numerous sinkholes of a size to be shown by topographic contours. Instead, there are relatively few, widely separated sinkholes which penetrate the Macedonia Bed (and whose swallets served as dye introduction points). Thus much of the paleovalley is underlain by areas in which the subsurface circulation is shallow (no deeper than the underlying Macedonia Bed) and relatively unmarked by the development of sinkholes. Although it is likely that deep circulation of meteoric water is generally absent beneath the Macedonia Bed in these areas, at least a few deeper conduits must exist, since several of the traced swallets are completely surrounded by such areas.

D. NORTHERN FAYETTE AND SOUTHERN SCOTT COUNTIES AREA

L. E. Spangler, J. W. Troester, and J. Thrailkill

This area is the largest studied in the Inner Bluegrass Karst Region. Field work was begun by J. W. Troester in the area of the city of Georgetown prior to the initiation of the Mercer County area, and the downstream portion of the Royal Spring basin and the adjacent Sharp Swallet basin was delineated. The remainder of the study (over 90% of the area) is the result of field work by L. E. Spangler.

D1. Groundwater Basins

A total of 105 dye introductions were made, of which 21 were not detected, 3 resulted in surface traces, 15 were downstream segments of serial traces, and 15 were duplicates. Most of the duplicate traces were the result of dye detection both at a karst window and a spring of dye introduced in several swallets upstream from the karst window. Nineteen groundwater basins were identified, and two traces were evaluated as too short and shallow to be considered groundwater basin flow. In the following discussion, an underlined designation following the name of a spring, groundwater basin, or used for a dye introduction point or trace identifies the feature on Fig. 2 and/or 4 and in Table 2 (see section B1 for more information). Dye introductions prefixed with "B" were conducted by Troester and those prefixed with "D" by Spangler.

D1a. Royal Spring Basin (29)

Royal Spring (29) is a smaller second magnitude spring, and is the largest investigated to date in the Inner Bluegrass Karst Region. It emerges at the head of a small pocket valley in the city of Georgetown and feeds a stream which flows to North Elkhorn Creek. It is the principal water supply for Georgetown.

Matson (1909, p. 80) reported an "examination" of Royal Spring using sodium chloride as a tracer, but gives no location information. Mull (1968, p. 15 and 17) believed that most of the flow of the spring was from the east along the surface divide between Cane Run and North Elkhorn Creek, and that some of its flow was from water sinking in swallets along Cane Run. Faust (1977, p. 13) outlined a large recharge area for Royal Spring which included the upper watersheds of Cane Run and North Elkhorn Creek. Although no water tracing experiments were performed in the studies of Mull and Faust, Mull (1968, p. 17) reported that chemical spills in the headwaters of Cane Run had been detected in the flow from Royal Spring.

Dye introduced at six swallets was detected at Royal Spring. The most northerly of these (B1) is in a deep sinkhole in the southern part of Georgetown, three (B8, D9, and D48) are in or within a few meters of the channel of Cane Run, and two (B7 and D90) are on tributaries of Cane Run near their confluence with it. In addition, there are a number of untraced swallets along the middle reaches of Cane Run and its tributaries, and all or portions of the flow of Cane Run is captured by the traced and untraced swallets along its channel depending on flow conditions and the capacity of the swallet.

The trace from the most distant swallet (D48) was more than 15 km, the longest yet conducted in the Inner Bluegrass Karst Region. This swallet is also of interest in that under some discharge conditions it functions as a spring, and is thus what has been termed an estavella. Despite an intensive search, no swallets have been located in the headwaters of Cane Run upstream from D48, which extend to the center of the city of Lexington, but the presence of storm sewers and other drainage modifications in this urbanized area make it difficult to say that none exist. There is a moderate size spring feeding Cane Run about 1500 m upstream from D48, and an undetected dye introduction, D41(X) (Appendix 1) was made in the headwaters of Cane Run to the southeast, but the amount of dye was probably insufficient for detection at Royal Spring

The six dye introduction points lie very nearly in a straight line (Fig. 4) which suggests a geologic control for the groundwater basin. Although this line is generally down the regional dip to the spring, it does not appear to follow local dip directions or the troughs of mapped synclines. An alternate explanation is that this line is a master joint, a series of closely spaced joints, or an unmapped fault.

Royal Spring emerges from the Grier Limestone Member about 5 m below its contact with the overlying Tanglewood Limestone Member and all six of the dye introduction points are in either the Grier or Tanglewood within

5 m of the contact, suggesting that the conduit or conduits may be developed within a rather narrow stratigraphic interval throughout the 15 km length of the groundwater basin. Also occurring within this interval is the roughly 2 m thick argillaceous Cane Run Bed. It is mapped about 10 m above the Tanglewood-Grier contact to the south (Miller, 1967) and 7 m above the contact to the southeast (MacQuown and Dobrovolney, 1968. Cressman (1965) puts it at the Tanglewood-Grier contact near Georgetown in the northern part of the groundwater basin. Although the Cane Run Bed does not appear to perch the subsurface conduit, since most or all of the traced swallets penetrate it, it may perch reaches of the surface channel of Cane Run, as suggested by Mull (1968). In the northern part of the basin, subsurface flow passes beneath the argillaceous Stamping Ground Member (so named by Cressman, 1973, but shown as the lower of two "fossiliferous limestone and shale" units on the geologic maps by Cressman, 1967).

D1b. Russell Cave Spring Basin (30)

A groundwater basin discharging at Russell Cave Spring (30) underlies an area of about 9 km^2 northeast of the city of Lexington. Of the seven dye introductions detected at the spring, three (D3, D5, and D24) were from swallets in residential suburbs of Lexington. Prior to performing these traces, it was thought that subsurface flow in this area was probably east to north Elkhorn Creek, and considerable time was spent trying to locate a spring near the creek upstream from Russell Cave Spring. No spring larger than Bryan Station Spring (7) which is small and apparently has only a local catchment area, was found.

The location of the Russell Cave Spring basin bears little relationship to surface drainage. The middle portion is in the Cane Run surface watershed, and swallets D5, D8, and D24 are in the paleovalley at a tributary to Cane Run. Deep Springs swallet (D3) to the south is in the North Elkhorn Creek surface drainage, and if subsurface flow from this swallet is in a straight line to Russell Cave Spring (for which there is no evidence), its conduit lies beneath the Cane Run-North Elkhorn Creek surface divide for about 3 km of its 7 km length. It is unlikely that the basin extends as far south as the watershed of Hickman Creek, which flows south to the Kentucky River. A dye introduction, D43(X) (Appendix 1), made into a large sinkhole just south of the apparent surface divide between North Elkhorn and Hickman Creeks was not detected, although it is not certain that enough dye was used if flow is to Russell Cave Spring.

The axis of a broad north-plunging anticline, which is the crest of the Cincinnati Arch, lies between the spring and all of the dye input points. Russell Cave and the accessible segment of the stream within it extends southwest of the spring for about 1.5 km following a line of sinkholes and crossing the axis of the anticline. If all of the dye traces to the spring flow to the cave stream at or upstream from the end of the accessible portion of the conduit, the flow from the swallets may be north along the west side of the anticline. This direction is the same as a number of small faults and barite veins shown on the geologic map.

Russell Cave Spring emerges from the Grier Limestone Member a few meters below its contact with the overlying Tanglewood Member, and the four swallets (D3, D5, D24, and D8) traced in the southern part of the basin are all in the Tanglewood. The argillaceous Brannon Member occurs at the base of the Tanglewood in the south, but is mapped within the lower Tanglewood at Joyland Cave (D5) and is absent to the north. It is probably penetrated underground by the conduit draining the Deep Springs swallet (D3) and there is no evidence that it influences subsurface flow, although it may perch the small surface stream in the blind valley which sinks at Joyland Cave (D5).

The lower tongue of the Millersburg Member occurs in the upper Tanglewood in the basin. This unit, which consists of about equal proportions of limestone and shale and is 4 to 7 m thick, crops out on ridges. It presence has not inhibited deep conduit development, since flow from traced swallets in the south must pass beneath areas where it is present. On the higher ridges, the upper tongue of the Millersburg is also found.

The southernmost trace in the area (D3) was introduced in Deep Spring swallet, which is less than 1 km from the Lexington Fault System, which trends northeast to cross North Elkhorn Creek a short distance upstream from Bryan Station Srping (7). Because it seemed likely that flow conduits would follow the large displacement faults in this system, dye was introduced in a swallet (D35) about 100 m northwest of the single fault that here represents the fault system. The trace was detected at Bailey Spring, only 400 meters away on the opposite (downthrown) side of the fault. The flow path was across the fault at nearly right angles and followed a small surface valley. Because the trace was so short and the subsurface path apparently so shallow, no groundwater basin was defined.

D1c. Vaughans Spring Basin (46)

Like the Russell Cave Spring basin, the Vaughans Spring basin (46) extends beneath the Cane Run-North Elkhorn Creek surface divide. It is of especial interest because its major subsurface conduit passes beneath North Elkhorn Creek. A dye introduction at Mallory Spring (D49a), a small high-level spring whose flow is diverted underground in the same sinkhole in which the spring is located, and dye introduced at two swallets farther north, was detected in McGee Sink (23), a karst window. McGee Sink lies on a well developed line of sinkholes which trends north to North Elkhorn Creek. Traces from McGee Sink (including those from dye introductions at other swallets) were detected at Vaughans Spring, which issues from a rise pool on the north side of North Elkhorn Creek and drains to the creek by a short channel.

Although subsurface flow conduits in other groundwater basins had been found to pass beneath small surface streams fed by high-level springs, this was the first instance of this phenomenon with a major perennial stream the size of North Elkhorn Creek. The mechanism by which this can occur is difficult to understand, especially since the major flow conduit from McGee Sink north to North Elkhorn Creek appears to follow a well developed line of sinkholes suggesting the presence of a vertical structural element.

The southernmost traced swallet in the basin, Mallory Spring (D49a), is in the Cane Run watershed and is located on a north trending fault. If the conduit from the swallet follows the fault to the north, it passes beneath nearly 10 m of argillaceous Millersburg Member where it crosses the surface divide.

A trace of only about 400 m length was made from a high-level spring and swallet (D16) in a springhouse to Paxton Spring (25), a high-level spring which drains on the surface to Cane Run. The flow path indicated by this trace, which is only a short distance south of Mallory Spring (D49a), was so short and shallow that no groundwater basin was defined.

D1d. Lindsay Spring (22) and Spring Lake Spring (40) Basins

Lindsay Spring (22) emerges from the Grier Limestone Member on the north side of Town Branch. Much of its groundwater basin underlies a valley to the north which is shown on the topographic map as containing a perennial tributary to Town Branch. Under normal runoff conditions, however, surface flow in the valley occurs only near it mouth and in a one kilometer portion of the valley between its emergence at Spring Lake Spring (39) and swallet D1d. Dye traces from swallets (D6 and D34) on the north side of the valley were detected at Lindsay Spring, indicating subsurface flow to the southwest at nearly a right angle to the trend of the surface valley.

A major portion of the flow of the larger third magnitude Lindsay Spring is contributed by swallet D1d which captures the flow of the smaller third magnitude Spring Lake Spring. Because of the 1 km length of surface flow between Spring Lake Spring and the swallet, the two areas of subsurface drainage were defined as separate groundwater basins. The Spring Lake Spring basin occupies the head of the valley in which the spring is located.

Spring Lake Spring flows from a rise pool at about the stratigraphic position of the argillaceous Cane Run Bed, which crops out a short distance down the valley. Flow in its basin is generally downdip, and subsurface conduits in the basin are probably perched on the Cane Run Bed, which would explain the location of the spring being some distance above the elevation of Town Branch, the major surface stream in this portion of the area.

The Spring Lake basin probably does not extend south into the surface watershed of upper Town Branch, since two unsuccessful dye introductions, D22(X) and D41(X) (Appendix 1) were made into a sinkhole about 1 km south of D12. Flow from this sinkhole is probably to an unlocated spring along Town Branch in a heavily urbanized portion of the city of Lexington.

In contrast, subsurface flow in the Lindsay Spring basin appears to completely disregard bedding attitude or the presence of argillaceous units. The three traces (D1d, D6, and D34)are across a small anticline nearly at right angles to its axis, and the flow conduits to Lindsay Spring pass beneath both the stratigraphic position of the Cane Run Bed and probably beneath the overlying argillaceous Brannon Member. These conduits also pass beneath a small surface stream fed by a high-level spring. Despite careful examination, no swallets were found anywhere along the stream.

D1e. Silver Springs Basin (35)

Silver Springs (35) is on the north side of the Town Branch valley about 4 km downstream from Lindsay Spring (22). Its groundwater basin extends more than 4.5 km northeast to swallet D65 in the surface watershed of Cane Run. Four closely spaced parallel faults cross the middle of the groundwater basin, and three dye introductions (D7, D13, D14) were made in sinkholes or short blind valleys on one of these northwest-trending faults. Although the trend of the faults parallels the apparent structurally controlled flow direction in the adjacent Royal Spring groundwater basin (29), flow from the three dye introductions is to the southwest, nearly at right angles to the faults.

About 1 km northeast of Silver Springs, the flow line from the above swallets passes beneath a small surface stream that shows no tendency to be diverted underground. At about the same point, the flow line crosses the axis of the same anticline described in section D1e, crosses a mapped barite vein at about a 45° angle, and probably passes near a mapped joint set. The indicated trend of the joint is nearly parallel to the flow direction, but none of the other structural features shown on the geologic map would seem to suggest the flow direction.

The surface divide between Town Branch and Cane Run is capped by an extensive area of argillaceous Millersburg Member, and the 7 m thick Greendale Lentil occurs in the upper part of the Lexington Limestone Member just beneath the Millersburg. The subsurface conduit conducting flow from swallet D65 passes beneath both of these argillaceous units, as well as crossing all four of the faults described above.

D1f. Slacks Spring Basin (36)

Under normal discharge conditions, Slacks Spring (36) emerges from a number of outlets below the water surface near the south bank of North Elkhorn Creek (making both discharge observations and dye detection difficult). During high flows, water rises at the end of a normally dry pocket valley to the south and follows a short channel to the creek. Flow from the upper portion of the groundwater basin is also accessible at or near the entrance to Slacks Cave (37) and at Sloanes Spring (38), a karst window at which the 9 upper basin traces were detected. The discharge at Slacks Cave could not be determined, and much of the flow does not appear at the surface at Sloanes Spring, as evidenced by the very low discharges observed during times of moderate runoff.

The Slacks Spring groundwater basin underlies most of the area between lower Cane Run and the Cane Run-South Elkhorn Creek surface divide, and the southern part of the basin extends into the Town Branch watershed. The major flow conduit in the basin appears to be nearly straight and to underlie a line of deep sinkholes from Slacks Spring (36) through the Slacks Cave entrance (37), Sloanes Spring (38), swallet D51a, as far south as the Fayette County line. A portion of this conduit is accessible for more than 2 km in Slacks Cave, where its cross-sectional area is as much as 50 m^2. This linear trend is very nearly parallel to that of the Royal Spring groundwater basin (29) 5 km to the east, and probably is controlled by a structural feature.

Although the general direction of flow in the basin is down the regional dip to the northwest, this dip is modified by a northwest-plunging syncline along lower Cane Run, resulting in northeast dip in the downstream part of the basin. As in the adjacent Royal Spring basin, the major flow conduit passes beneath the Stamping Ground Member. Both the Cane Run Bed and Brannon Member are missing, and the Millersburg Member is restricted to isolated outcrops along the southwestern margin of the basin, preventing any conclusions to be drawn of the influence of these three argillaceous units on the subsurface flow.

D1g. Gano Spring Basin (15)

Gano Spring (15) emerges from the west bank of a small stream about 2 km distant, and 10 m above, its confluence with South Elkhorn Creek, and the groundwater basin appears to underlie the headwaters of the stream. Hence it resembles the Spring Lake Spring basin (39), whose subsurface flow is believed to be downdip in conduits perched on an argillaceous unit (see section D1d). It differs, however, in that a major portion of the flow (from D37 and D47) is along strike, and that no argillaceous unit is indicated as being present at the stratigraphic position of the spring, 10 m below the top of the Grier Limestone Member. While this is near the stratigraphic horizon of the Macedonia Bed in the northern part of the Northeast Woodford County area (section B2c), the nearest mapped occurrence of this unit is about 8 km west of Gano Spring.

D1h. Nance Spring Basin (24)

The Nance Spring groundwater basin (24) has several interesting characteristics. The three traces to Nance Spring were along a northwest-trending line nearly parallel to the trend of the principal subsurface conduit in the Slacks Spring basin (36) 2 km to the east. For about one-half the distance from the spring, this line follows a mapped fault with up to 25 m of displacement. This fault, which is shown terminating just south of D64, is the northeast border fault of the Switzer Graben (Black, et. al., 1977). To the south, this trend is indicated by a line of sinkholes.

Although its traced groundwater basin lies south of North Elkhorn Creek, Nance Spring emerges from outlets in the bed of North Elkhorn Creek within a few meters of its north bank, directly on the mapped trace of the fault.

It is of interest to note that the southern-most swallets D70 and D78 are in the surface watershed of, and less than 2 km distant from, South Elkhorn Creek. In this area, South Elkhorn Creek is about 10 m higher than North Elkhorn Creek at Nance Spring, and the flow conduit in the Nance Spring basin may someday serve as a subsurface capture route. A dye introduction, D73 (X) (Appendix 1) in a swallet only 500 m west of D78 was not detected at Nance Spring. This suggests the existence of a groundwater basin with southwest flow to an unknown spring on South Elkhorn Creek, which would make such a capture even more likely.

D1i. Smaller North Elkhorn Creek Basins: Sharp Swallet (B3), Holland Spring (18), Tevis Spring (43)

Three small groundwater basins discharging at springs along North Elkhorn Creek between Royal Spring (29) and Vaughans Spring (46) were identified by one or two traces each. The Sharp Swallet basin (B3) is the most northerly of these and the most intensely investigated. As discussed in section D1a, Mull (1968) had suggested that the Royal Spring basin extended east beneath the Cane Run-North Elkhorn Creek surface divide, and that major conduits carrying flow to Royal Springs existed in this area. A site between B1 and B3 was being proposed for industrial development, and the presence or absence of such conduits beneath the site became a major environmental question in the city of Georgetown.

Two dye introductions (B4 and B6, Appendix 1) into possible swallets on the site did not result in subsurface traces, but B3 indicated flow is northwest to North Elkhorn Creek. The spring discharging this Sharp Swallet basin has not been located with confidence, but positive dye detection in North Elkhorn Creek to the northwest, but not to the north, indicates the configuration of the lower portion of the basin to be about as shown on Fig. 4. This dye trace information combined with well data led to the conclusion that deep conduits to Royal Spring did not exist beneath the site, although surface flow from that portion of it west of the surface divide would be into sinkholes and swallets (such as B1) in the Royal Spring Basin. A more complete discussion of this investigation will be found in Thrailkill and Troester, et. al (accepted for publication).

The trace from swallet B3 followed a small fault, which also extends southeast along a line of sinkholes, none of which contain swallets into which dye could be introduced. A dye introduction (D14) into a swallet slightly northeast of this trend was detected at Holland Spring (18), indicating flow to the northeast in minor groundwater basin beneath a surface watershed. A similar small basin drains to Tevis Spring (43) southeast of the Holland Spring basin.

D1j. Smaller South Elkhorn Creek Basins: Ansley Swallet (D57), Santen Spring (31), Elkhorn Spring (13), Cornett Spring (10)

Four small groundwater basins along South Elkhorn were indicated by traces in western Scott County. The most southerly was outlined on the basis of a single trace from Ansley Swallet (D57). The spring was not located and the trace was detected in South Elkhorn Creek a few hundred meters downstream from the mouth of Twon Branch. Although the basin is shown on Figure 2 as discharging into South Elkhorn Creek, it is equally likely that the discharge is into Town Branch.

The Santen Spring basin (31) was defined by three traces to Santen Spring, which issues from a rise pool a few meters from South Elkhorn Creek. The spring is near the mouth of a surface valley with little or no surface drainage, and the groundwater basin indicated by the dye input points appears to underlie the valley. Elkhorn Spring (13) receives the drainage of a small valley to the north through a conduit beneath a surface divide, and its groundwater basin may border the Nance Spring basin (24). To the east, Cornett Spring (10) has a groundwater basin which appears to trend northwest.

Santen, Elkhorn, and Cornett Springs all issue from the Grier Limestone Member from 10 to 20 m below its top. Although the argillaceous Macedonia Bed occurs in this interval elswehere, it is not mapped at the springs and the considerable stratigraphic range of the spring outlets makes it unlikely that they are perched on a single unit. The single swallet (D52) traced to Cornett Spring is in a line of sinkholes that trends northwest from the spring as far as the south border fault of the Switzer Graben (see section D1h). This trend is nearly parallel to others in basins to the east (e.g., Nance Spring basin, 24, Slacks Spring basin, 37). It is worth noting that the Cornett Spring basin does not extend the length of this line of sinkholes, however. Three dye introductions, D59 (X), D69 (X), and D75 (X) (Appendix 1) were made in one swallet along this line less than 500 m northwest of D52 but were not detected at Cornett Spring.

D1k. Other Basins: Jennings Spring (21), Steeles Spring (41), Blue Spring (4)

The Jennings Springs basin (21) was indicated by a single trace to a spring on lower Cane Run. Two other basins were outlined based on traces conducted outside the area of study, in both cases to identify the direction of flow of streams in caves. The Steeles Spring basin (41) in Fayette County south of Town Branch was indicated by traces from two caves to Steeles Spring, and the Blue Spring basin (4) in Scott County north of North Elkhorn Creek was identified by a similar trace from a cave stream to Blue Spring.

D2. Discussion

Many of the relationships noted in the Northern Fayette and Southern Scott Counties area were similar to those in the Northeast Woodford County area (see section B) and Mercer County area (section C). Other phenomena had not previously been observed, however, and the size of the area and the substantial time and effort devoted to its investigation have led to further insights into the nature of subsurface flow in the Inner Bluegrass Karst Region.

D2a. Relationship Between Surface and Subsurface Flow

The correspondence (or lack of it) between surface and subsurface drainage areas in the Northern Fayette and Southern Scott Counties areas is similar to that in the other areas studied. Except for the Lindsay Spring basin (22), all groundwater basins with areas of 5 km^2 or more are located beneath more than one major surface watershed (e.g., Cane Run and Town Branch, North Elkhorn Creek and Cane Run). Some of the smaller groundwater basins underlie surface drainage basins (e.g., Gano Spring, 15; Santen Spring, 31) while others do not (e.g., Ansley Swallet, D57; Elkhorn Spring, 13).

The relationship of Cane Run to the Royal Spring groundwater basin (29) deserves special mention because of its importance to a municipal water supply and because it is a phenomenon not previously encountered in the region. The headwaters of Cane Run are in the city of Lexington and believed to be largely at the surface, although this area has not been studied. Likewise, its lower course in Scott County above its confluence with North Elkhorn Creek is also one of mainly surface flow. North of Lexington in Fayette County, however, it overlies one or more major flow conduits in the Royal Spring groundwater basin, and its surface flow is diverted underground by a number of swallets within or adjacent to its channel. Thus under any but high discharge conditions which exceed the capacity of the swallets, all of the surface flow of Cane Run in Fayette County is routed underground to Royal Spring in the city of Georgetown.

A second phenomenon of significance not observed in other areas is that of subsurface flow passing beneath major surface streams. This is best shown in the Vaughans Spring groundwater basin (46) where flow from a major groundwater basin to the south emerges in a rise pool adjacent to the north bank of North Elkhorn Creek. Such subsurface flow also occurs in the Nance Spring basin (24) where flow from a basin to the south rises in the bed of North Elkhorn Creek adjacent to the north bank.

D2b. Influence of Structural Factors

The overall direction of flow in three of the larger groundwater basins in the area (Royal Spring, 29; Slacks Spring, 36; and Nance Spring, 24) are approximately parallel to the regional dip. In three others, however (Gano

Spring, 15; Silver Springs, 35; and Lindsay Spring, 22), flow is more nearly at right angles to the regional dip. In the two remaining large basins, major flow in the Vaughans Spring basin (46) is slightly east of north and in the Russell Cave Spring basin (30) it crosses the reversal of regional dip along the crest of the Cincinnati Arch.

There is even less reason to believe that local dip exerts a significant influence on flow directions in most basins. The various relationships are discussed for individual basins in section D1, and can be summarized simply by stating that although in a few basins (e.g., Spring Lake Spring, 39) flow appears to be down the local dip, in the majority (e.g. Lindsay Spring) there was no consistent relationship.

In two basins (Nance Spring and Sharp Swallet, B3) dye trace flow lines were along mapped faults. In two other instances (Silver Springs basin and Bailey Spring Trace, D35), traced flow lines were directly across faults. Elsewhere (e.g., Vaughans Spring basin), flow from traced swallets may follow faults, but overall it does not appear that such mapped features are a reliable indicator of flow direction in the absence of indicators from other sources.

The strongest correlation of what is probably a structural feature and subsurface flow directions is with aligned sinkholes. Such trends appeared to be underlain by major conduits in several, but by no means all, of the groundwater basins identified. These include the Cornett Spring (10), Nance Spring, Slacks Spring, Royal Spring, Sharp Swallet, Vaughans Spring, and Russell Cave Spring basins. Furthermore, the near parallelism of at least portions of these basins in the northwest part of the Northern Fayette and Southern Scott counties area is striking.

D2c. Control of Subsurface Flow by Argillaceous Units

All seven argillaceous limestone units within and above the Lexington Limestone are mapped in portions of the area except the Macedonia Bed, which may be present even though not mapped. The Clays Ferry Formation crops out at higher elevations on the downstream side of faults adjacent to the Nance Spring basin (24) and Bailey Spring (see section D1b), and its influence on subsurface flow cannot be evaluated. The Millersburg Member caps many of the higher ridges in the eastern part of the area, and major flow conduits in the Russell Cave Spring (30), Silver Springs (35), and probably the Vaughans Spring (46) basins are present beneath it. Conduits in the Silver Spring basin also pass beneath the restricted Greendale Lentil. Flow in the lower portions of the Royal Spring (29) and Slacks Spring (36) basins is beneath the lithologically similar but stratigraphically slightly lower Stamping Ground Member.

The Brannon Member is present only in the southern portion of the area. Major flow conduits in the Lindsay Spring basin (22) occur beneath this unit, as well as the underlying Cane Run Bed. Flow beneath the Cane Run Bed also occurs in the Royal Spring basin, but this unit appears to perch flow in the Spring Lake Spring basin (39). The lowermost argillaceous unit in the areas studied, the Macedonia Bed, is not mapped in the Northern Fayette and Southern Scott counties area, but it is possible that it is present at, and perching, Gano Spring (15) and its groundwater basin. Although most of the major conduits and springs are in the upper Grier Limestone Member, some near the stratigraphic position of the Macedonia Bed, the stratigraphic range of these features is too large to ascribe their position to an argillaceous unit.

D2e. Nature of Groundwater Basins

Observations made in the central portion of the Northern Fayette and Southern Scott counties area allowed the inferences drawn for the Sinkhole Plain paleovalley in the Mercer County area to be confirmed and expanded. As discussed in section C2c, although the Sinkhole Plain paleovalley is drained by four groundwater basins, there are extensive areas within it where subsurface flow is perched on the argillaceous Macedonia Bed. Flow in these areas is in small, shallow conduits, with the only deep circulation of meteoric water occurring at the few places where deep conduits from major swallets are developed beneath the Macedonia Bed.

Because it was hoped that the divides between major groundwater basins in the central part of the Northern Fayette and Southern Scott counties area could be located with some precision, an intensive search was conducted to locate swallets in the areas between the basins outlined on Fig. 2 and 4. It was concluded, however, that only very small swallets and shallow sinkholes were present in these areas, and any subsurface flow was shallow and emerged at high-level springs. Thus, the situation is similar to that found in the Mercer County Area, except that such shallow subsurface flow, which probably is at and just beneath the contact of the regolith with underlying bedrock, is not relatable to a mapped argillaceous unit and occurs over a wide stratigraphic interval.

Observations were also made which indicated other characteristics of groundwater basins. Based both on the relative elevation of swallets in topographically low areas and major springs, and on examination of conduits underground, major flow conduits in the groundwater basins appear to have low gradients. Further, although the nature of flow beneath swallets is generally unknown, in the few cases where the conduit conducting flow from a swallet can be observed, it is usually steep and in some cases vertical. Thus groundwater basins appear to have rather flat floors and steep margins.

E. WALNUT HILL AREA

D. R. Gouzie and J. Thrailkill

A small area in Fayette County southeast of Lexington was studied to investigate the importance of faulting as a control of groundwater basin flow.

E1. Groundwater Basins

Two small groundwater basins were identified by two original dye introductions. In the following discussion, an underlined designation following the name of a spring, groundwater basin, or used for a dye introduction point or trace identifies the feature on the inset map on Fig. 4 and in Table 2 (see section B1 for more information).

E1a. Boggs Spring Basin (5)

A single trace (E1) was made from a swallet in a sinkhole to Boggs Spring (5). The sinkhole had contained a pond, which drained suddenly more than a year before trace E1 was conducted, and a large flow of turbid water was reported to have issued form the spring. The trace confirmed this flow connection.

E1b. I-75 Pond Spring Basin (20)

A dye introduction (E2) was made in a deep sinkhole 1 km east of E1. It was detected at I-75 Pond Spring to the southeast, and indicated the presence of a second groundwater basin.

E2. Discussion

Both dye traces were conducted in a highly faulted area. The major faults define two narrow east-west trending grabens joined end to end, and other faults radiate to the south and southeast from the grabens (Black, 1967). The centers of the grabens are dolomite, which is probably of replacement origin related to the faulting (Black, et. al., 1981).

Swallet E1 is on the north fault of the western graben, but the conduit which drains it follows the fault for only a short distance if at all. In order to emerge at Boggs Spring (5), which is about 1 km south of the graben, flow crosses the belt of dolomite and must pass beneath both the Millersburg Member and the underlying Brannon Member, both of which are argillaceous units.

Dye introduction (E2) was on the south fault of the eastern graben, and also adjacent to a dolomite body. Flow in this area is along the graben to I-75 Pond Spring in the graben to the east. Only the western end of this eastern graben is dolomitized, and the argillaceous Clays Ferry Formation and Millersburg Member are mapped within the graben between E2 and I-75 Spring.

The relationship of subsurface flow to faulting in the Walnut Hill area can thus only be described as ambigious. While the flow in the I-75 Pond Spring basin (20) follows the fault trend, flow in the Boggs Spring Basin (5) does not, and a subsurface divide is present along the fault trend.

F. SUBSURFACE WATER IN THE INNER BLUEGRASS KARST REGION

J. Thrailkill

F1. Groundwater Basins

The present study has shown that the major flow of subsurface water in those portions of the Inner Bluegrass Karst Region investigated is in at least 38 individual basins. The term groundwater is usually reserved for potable water in saturated voids which is beneath the potentiometric surface and hence at pressures greater than atmospheric. Because these basins contain such water, they will be referred to as groundwater basins although much of their flow is unsaturated and above the potentiometric surface in what is termed the vadose zone. These concepts will be discussed later.

Flow within each basin is dendritic, in that recharge from swallets, sinkholes, and eleswhere, successively coalesces to emerge at a spring which drains the basin. A few such springs, such as Roaring Spring, Burgin Spring, and Cove Spring (refer to Table 2 and Appendix 3 for the location and other information on springs and groundwater basins) have multiple outlets, usually within a few tens of meters of each other, in two or more of which dye was detected during some traces. In no instance, however, did dye detections indicate flow between adjacent basins. In a few basins, (Roaring Spring, Distillery Spring, Slacks Spring, and Vaughans Spring basins), major flow appears at the surface at the bottom of deep sinks (karst windows), and discharge from Spring Lake Spring feeds a surface stream which flows into a swallet of the Lindsay Spring basin.

Although groundwater basins are a fundamental element of the hydrogeology of the region, they have been little discussed by previous workers. Palmquist and Hall (1961, p. 14) considered groundwater in the entire Blue Grass Region (including the Inner Bluegrass Karst Region) to occur in small, self-contained units which, with few exceptions, concide with surface watersheds. Faust (1977, p. 12-13), outlined the recharge areas of selected points, including Royal, Spring Station, and Versailles springs. He states that such recharge areas generally coincide with surface drainage basins and apparently based his delineation of recharge areas both on topography and his potentiometric surface map.

F1a. Basin Identification, Size, and Location

Outlines of the 38 basins (Fig. 2, 3, 4) were drawn to enclose swallets from which dye traces were made to major springs. Although subsurface drainage from untraced swallets within the basins as outlined probably also discharges at the spring, details of basin shape are largely unknown, especially for basins identified by only a single dye trace.

The area of each basin (Table 2) was estimated from the area outlined on the maps (Fig. 2, 3, 4) and ranges from less than 0.5 km^2 up to 15 km^2 for the two largest. It should be emphasized that the areas given are thus those which are believed to be underlain by an integrated conduit system, and that the catchment area of the spring is usually much larger, since it includes areas of shallow subsurface or surface flow outside the basin boundaries. The areas given in this report (Table 2) are thus generally much smaller than earlier estimates (Spangler and Thrailkill, 1981; Thrailkill, et. al., 1981; Spangler, 1982) which were based on the catchment area. These relationships are shown in Fig. 5.

In one location where surface flow was observed between a spring (Spring Lake Spring) and a swallet (in the Lindsay Spring basin), the length of the surface flow path suggested that the two basins should be identified separately. In the other instances where such flow is seen, it is in the bottom of a deep sinkhole or a blind valley and the feature considered a karst window within the basin. Groundwater basins were not defined for the short dye traces to Bailey and Paxton Springs because of lack of evidence of the existence of deep integrated flow conduits considered characteristic of groundwater basins.

Some of the smaller groundwater basins appear to underlie surface drainage basins (e.g., Baker Cave, Gano Spring, and Santen Spring basins), while others do not (e.g., Cove Spring, Elkhorn Spring, and Sharp Swallet basins). At least some flow indicated by dye traces in all of the larger basins (5 km^2 or more in area) passes beneath surface divides, and the shape of most larger basins shows little correspondence to present or inferred former surface drainage (e.g., Roaring Spring, Slacks Spring, Russel Cave, and Burgin Spring basins). In a few basins (e.g., Lindsay Spring and Vaughans Spring basins), underground flow is known to pass beneath perennial surface streams.

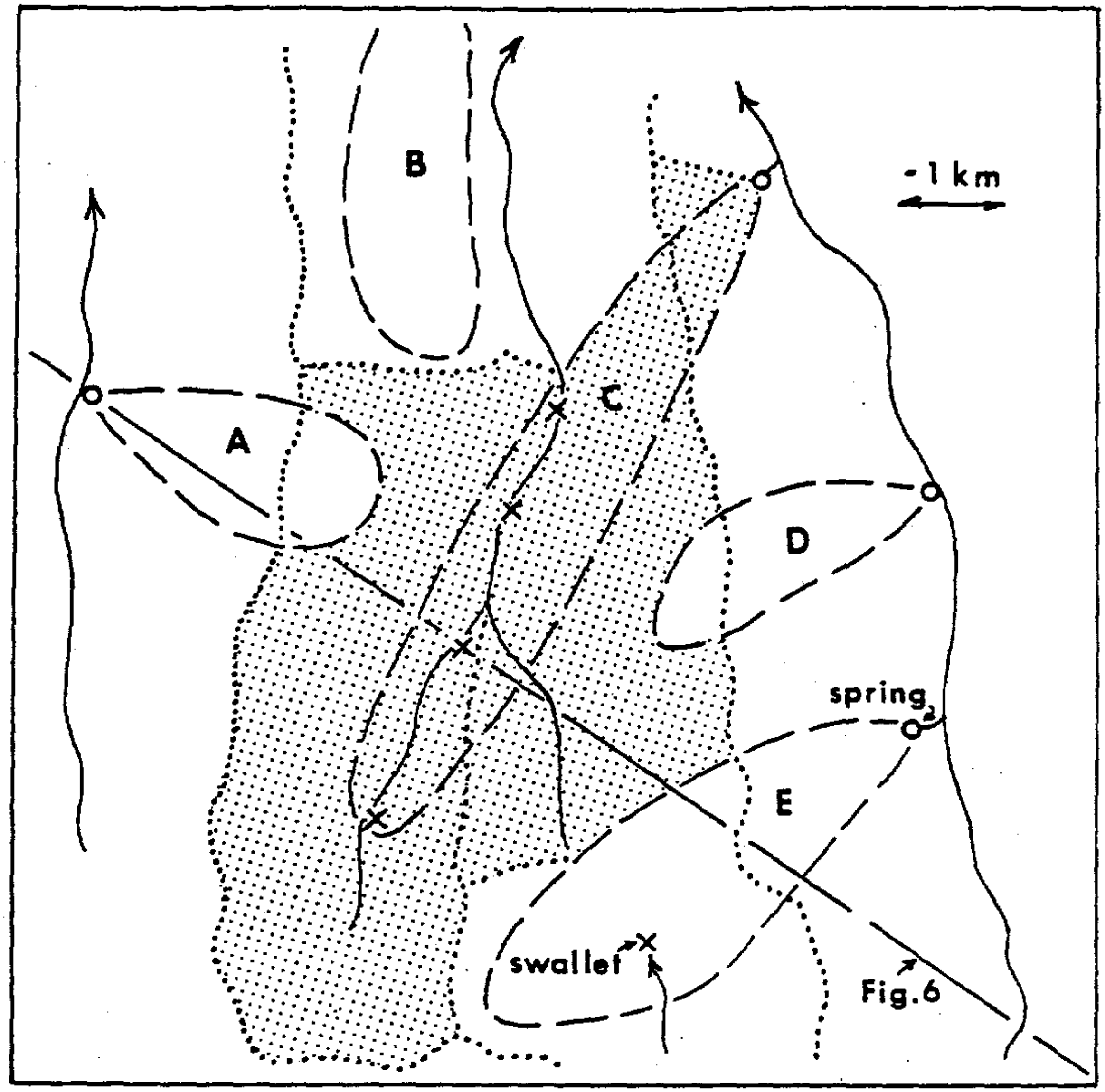

Figure 5. Map showing relationship of groundwater basins (dashed outlines) to surface streams (solid lines) and surface divides (dotted lines). Catchment area of spring C shown by dotted patterns. Although diagrammatic, map approximates the eastern portion of the Northern Fayette and Southern Scott counties area where A through E are the Silver Spring , Slacks Spring, Royal Spring, Vaughans Spring, and Russell Cave Spring basins, respectively.

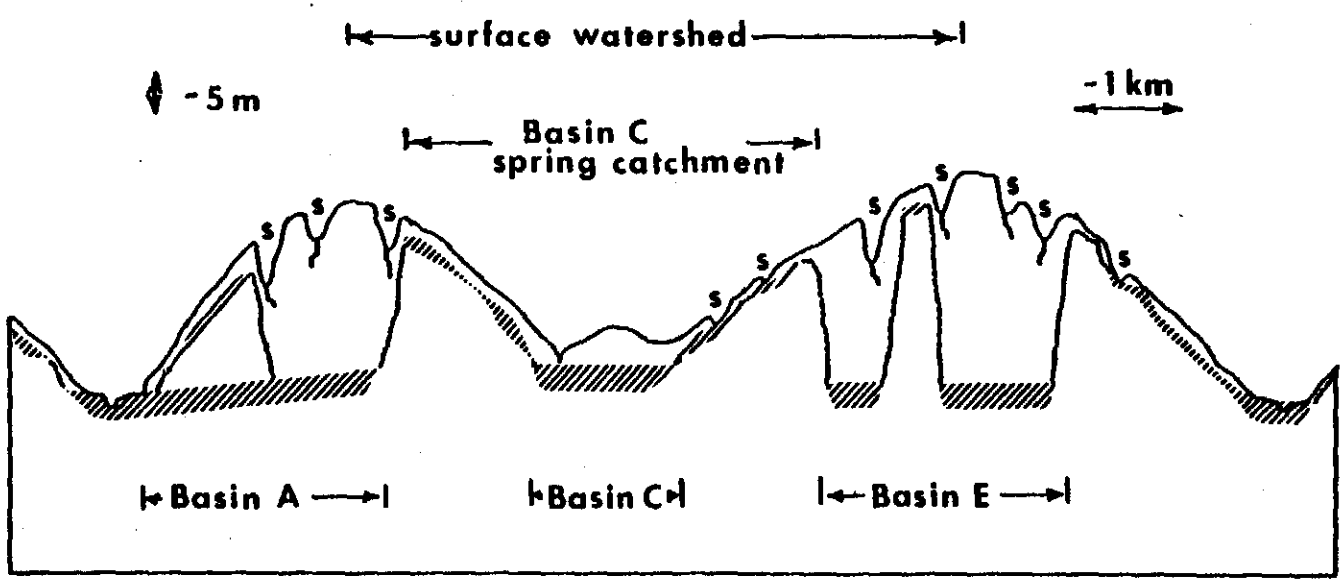

Figure 6. Cross section of groundwater basins and interbasin areas along line on Fig. 5 showing aquifer (lined pattern) and base of zone of meteoric water circulation (lower limit of lined pattern and dashed line). Note portions of basins A and C with interbasin area characteristics (penetrated by deep flow in basin A). The relationship of basin C to the catchment area of the draining spring and the surface watershed of the stream which overlies it is also shown. Sinkholes indicated by S. Vertical exaggeration approximately 100X.

F1b. Interbasin Areas and Basin Shape

Relatively few dye traces were conducted in the Northeast Woodford County and Walnut Hill areas, and further work would probably result in the enlargement of the known groundwater basins and the discovery of new basins. While similar results would be likely near the margins of the Mercer County area and the Northern Fayette and Southern Scott County area, intensive reconnaissance in the central portion of these areas (especially the latter) has shown that swallets are much less common between the outlined basins. Furthermore, dye introduced in such swallets emerged at small springs a short distance down slope after following shallow flow paths. Examples of such traces (none over 500 m long or with a vertical drop of more than 3 m) were D16 to Paxton Spring and D35 to Bailey Spring.

This absence of deep, integrated, subsurface drainage between basins is more marked than the simple reduction in size of conduits that might be expected as the divide between basins is approached, and the term interbasin areas will be used for these portions of the region.

Within interbasin areas, infiltrating water from slopes and shallow sinkholes is believed to flow in small conduits at or just below the interface between the bedrock and overlying regolith. Flow is generally down the topographic slope and emerges at small, often ephemeral, high-level springs. Streams fed by such springs generally flow on the surface but may be diverted into shallow subsurface conduits adjacent to the stream channel for short distances. If and when such a stream enters a groundwater basin, its flow is diverted underground by a swallet to emerge at a major spring, often several kilometers distant.

The bottoms of most of the major stream valleys (e.g., South Elkhorn Creek, North Elkhorn Creek, Town Branch, lower Cane Run, and the Salt River) appear to lie in interbasin areas. Faust (1977, p. 12 and plate 3) described losing reaches on both North and South Elkhorn Creeks, and gaging stations on these creeks not uncommonly report no surface flow (U. S. Geological Survey, 1981, p. 183-184). It is likely, therefore, that a portion of the flow of the major surface streams is diverted into conduits through swallets in the channel and return in inconspicious springs in the stream bed. Such conduits are probably shallow, as are the conduits in interbasin areas at higher elevations, but may be of considerable size because of the larger flow volumes. They are probably present mainly in the vicinity of the channel, but may cut across bends and meander loops.

Thus while there is only shallow subsurface flow in interbasin areas, they form part of the catchment area of major springs draining groundwater basins, with the boundaries between adjacent catchment areas within an interbasin area probably conforming closely to surface divides.

Although the shallow subsurface flow described above is characteristic of interbasin areas, it also occurs within the basins as outlined on Fig. 2, 3 and 4. As an example, the traced swallets in the Shawnee Run Spring basin are fed by flow from high level springs within the basin, and there appear to be extensive and numerous areas of such shallow subsurface flow within many of the basins. An alternative way of depicting such basins would be as narrow strips adjacent to the major flow conduits, but since the location of these conduits is generally unknown, and because there is some evidence from wells that at least the Slacks Spring basin is developed over a considerable area, as discussed below, this was not done.

Attempts to more closely define the boundaries between basins and interbasin areas were also complicated by evidence that such boundaries cannot be simply depicted in two-dimensions because basin flow conduits appear to be developed beneath what appear to be interbasin areas in a few cases. This is illustrated by the Lindsay Spring and Silver Springs basins, in which the major flow conduit passes beneath streams (fed by high-level springs) which remain entirely on the surface.

In contrast to the conduits in upland interbasin areas which are just beneath and roughly parallel to the land surface, the major flow conduits in groundwater basins appear to have gradients similar to surface streams and thus are nearly horizontal and only slighly above the level of the discharging spring. Although the path followed by water immediately after it enters a swallet is usually unknown, in the few instances where it can be observed in caves and pits it is usually steep and often nearly vertical. Such high-gradients were observed as often near the margins and upstream portions of basin as in the center and downstream portions.

The evidence available therefore suggests that the base of the zone of active meteoric water circulation is nearly flat in groundwater basins (and as much as 30 m deep beneath topographically high areas), rises abruptly at basin margins, and is within a few meters of the surface in interbasin areas. Thus groundwater basins in the Inner Bluegrass Karst Regions are believed to resemble "U-shaped valleys" as shown in Fig. 6.

F2. Basin Area and Spring Discharge

Numerous attempts were made during the course of the investigation to utilize observations of spring discharge as an additional parameter (other than dye tracing results) to estimate basin area. Although large amounts of discharge data were collected while dye tracing was underway, its nature was such (as discussed earlier under methods) that its utilization in this report is limited to assignment of spring magnitudes based on median dishcarges. More extensive analysis, including hydrographs for some springs, will be found in McCann (1978) and Spangler (1981).

The discharge of a spring is obviously a function of its catchment area and not of the area of its groundwater basin. Because the extension of the catchment area into adjacent interbasin areas is believed to be topographically controlled, as previously discussed, it should be possible to outline it with some accuracy for springs whose basin boundaries are well established. This has not yet been done, however, both because of uncertainties in the boundaries of most basins and because a relationship, even if only empirical, was wanted with basin area, not catchment area. It is realized, of course, that a consistent relationship between spring discharge and basin area requires a constant relationship between the areas of basins and catchments which is unlikely to exist.

Basin area and median spring discharge for the 30 basins (and portions of basins) for which both values are available are plotted in Fig. 7. In 21 of these, the relationship of 20 liters per second median discharge per square kilometer of basin area fits the data. In the remaining nine, it appears the spring is too small or the basin to large. For the three smaller basins: Tevis Spring (43), Pin Oak Spring (26), and Spring 13 (44) basins, it is likely that the outlined basins are too large, and this explanation probably holds for the Silver Springs basin (35) as well. The basin area assigned to Gay Sink Spring (16), Spring Station Spring (40), and Sloanes Spring (38), is that part of a larger basin which is upstream from these springs, which are all in karst windows where it is likely that only a portion of the flow emerges at the surface. The discharge of Slacks Spring (36), which emerges on the bank and in the bed of North Elkhorn Creek, has probably been underestimated. There seems to be no simple explanation for the apparent low discharge of Burgin Spring (8), however, since its groundwater basin seems to be fairly well defined.

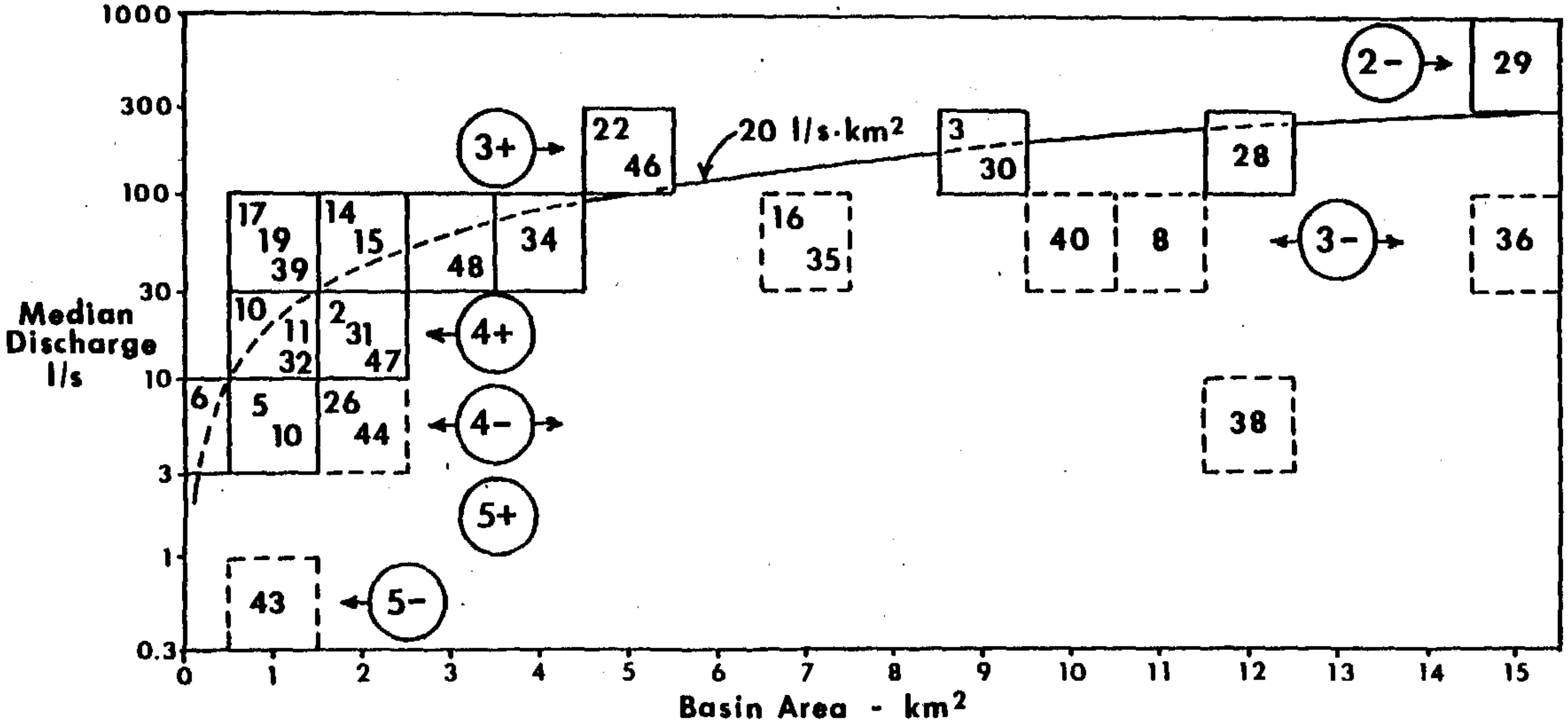

Figure 7. Relationship between groundwater basin area and median discharge of spring (Table 2). Circled numbers are spring magnitudes (e.g., 3- is smaller third magnitude). See section F2 for discussion.

The value of 20 $l/s\text{-}km^2$ used in the previous evaluation is about 6% of the 115 cm/yr average precipitation for the region. No particular significance should be attached to this value, both because of the unknown relationship between basin and catchment area discussed above, and because of the nature of the discharge data. The spring magnitude scale is logarithmic and the mean discharge, which would be most closely related to precipitation and basin area, is larger than the median discharge by an amount which is a function of the discharge distribution. An inspection of the individual data (Appendix 4) suggests a log-normal distribution, but the quality of the data is not really sufficient to pursue this further.

F3. Groundwater Basins and Karst Landforms

The Inner Bluegrass Karst Region is so named because of the presence of landforms which characterize a karst topography. As with other karst areas, the most abundant such landforms are <u>sinkholes</u>, the distribution of which was used to define the area of the region, and which will be discussed in some detail below.

In addition to sinkholes, four other karst landforms are found in the region. <u>Blind valleys</u> terminate downstream as the entire flow of a surface stream is diverted underground. <u>Pocket valleys</u>, on the other hand, begin abruptly upstream at a major spring. Depressions in which a major underground flow emerges at the surface as a spring and is then diverted underground are termed <u>karst windows</u>. The length of the surface flow varies from what appears to be a pool in the bottom of a deep sinkhole (e.g., McGee Sink) to a stream several hundred meters long flowing in what may be described as a combination of a pocket valley and a blind valley (e.g., the channel below Spring Station Spring). The flow in these landforms is major subsurface flow at or very near the potentiometric surface, and the numerous sinkholes in the region which contain a small stream fed by a high-level spring which sinks in the bottom of the sinkhole are not karst windows. Finally, what are here termed <u>paleovalleys</u> appear to be normal surface valleys but contain no surface stream channel. They usually contain a series of sinkholes in their bottom, and apparently formed when their surface stream was diverted underground at several points along its course, forming a series of blind valleys, followed by complete abandonment of surface flow except possibly during high discharge events.

Except for some sinkholes, all five of these landforms are the result of deep circulation of subsurface water, and their presence in an area should indicate the existence of a groundwater basin, allowing the location and extent of basins to be at least estimated from an examination of the topographic maps. Although some correlation appears to exist, it has not been possible to rely heavily on it because of sinkhole modifications and the inadequacy of available maps. Before examining these factors further, a discussion of the origin of sinkholes in the region is appropriate.

F3a. Sinkhole Origin

Contrary to widely held and stated opinion, the collapase of the roofs of caves is not the principal cause of sinkholes in the region (nor, for that matter, in any other karst area with which the author is familiar). Of the many sinkholes examined in the region, cave roof collapse is not believed to be a major facotr in the origin of any. Rather, they are produced by solution of the limestone bedrock at the contact with the overlying regolith by water which has infiltrated from the surface, the same process that occurs nearly everywhere in the region and has probably been the principal agent in the lowering of the bedrock surface through time.

Although there will be some penetration of the bedrock under a hill slope through many closely spaced, very small diameter conduits, solution at the base of the bedrock will be accelerated in the vicinity of the larger conduits and the more rapid lowering of the bedrock interface nearby will cause the capture of more flow from adjacent conduits, and hence increased bedrock solution. When the resulting subsidence of the overlying regolith (which initially is reflected by a simple flattening in the surface slope) is sufficient to reverse the downhill slope, a topographic depression is formed and a type one sinkhole results.

The existence of a topographic depression will further accelerate the enlargement of the conduit, since most of the water which infiltrates the surface within the depression will flow through it (although some of the flow will probably still be carried by smaller conduits). Major deepening and widening of the sinkhole will probably not occur, however, until the conduit becomes enlarged by solution throughout its length to the degree that the water flowing through it can transport particles of regolith, after which time the depression becomes a type two sinkhole. The volume of regolith removed may now exceed the amount of limestone dissolved, to the extent that bedrock is exposed on its sides or bottom. Although it seems likely that a topographic depression is generally formed prior to the onset of regolith removal (i.e., type one precedes type two), this may not always be the case, especially since the general downslope movement of regolith on hillslopes will tend to fill type one depressions or prevent them from forming.

A type three sinkhole is formed when the conduit is large enough and flow velocities high enough for insoluble or otherwise resistent beds which tend to perch the conduit are eroded through. Type three sinkholes have steep or near vertical drains to depth and their flow is integrated into the dendritic system of a groundwater basin. The various types of sinkholes are shown on Fig. 8.

Conduits draining type one and type two sinkholes, as well as those draining pre-type one areas (incipient sinkholes), are usually nearly horizontal, as would be expected from their being perched on resistent beds. They emerge on nearby hillslopes or the heads of small valleys as small, often ephemeral, high-level springs, some of which become turbid during high discharges, indicating the sinkholes they drain have reached the type two stage.

Type one and type two sinkholes are found throughout the region, both in groundwater basins and interbasin areas, and imply no deep circulation of subsurface flow. Type three sinkholes, on the other hand, do characterize groundwater basins.

The tendency of sinkholes to occur along former lines of surface drainage is due mainly to their development being favored by the increased infiltration and subregolith flow in such areas. In some cases, however, the location of such drainage lines was controlled by reduced resistence to erosion of the bedrock due to jointing or other factors, which would also promote more rapid conduit enlargement.

Returning to the idea that sinkholes are due to the collapse of cave roofs. The growth, and especially the deepening, of a thpe three sinkhole obviously is highly dependent on the efficiency with which regolith and other debris can be removed through its near vertical drain. Sinkholes located above conduits in the underlying groundwater basin system need

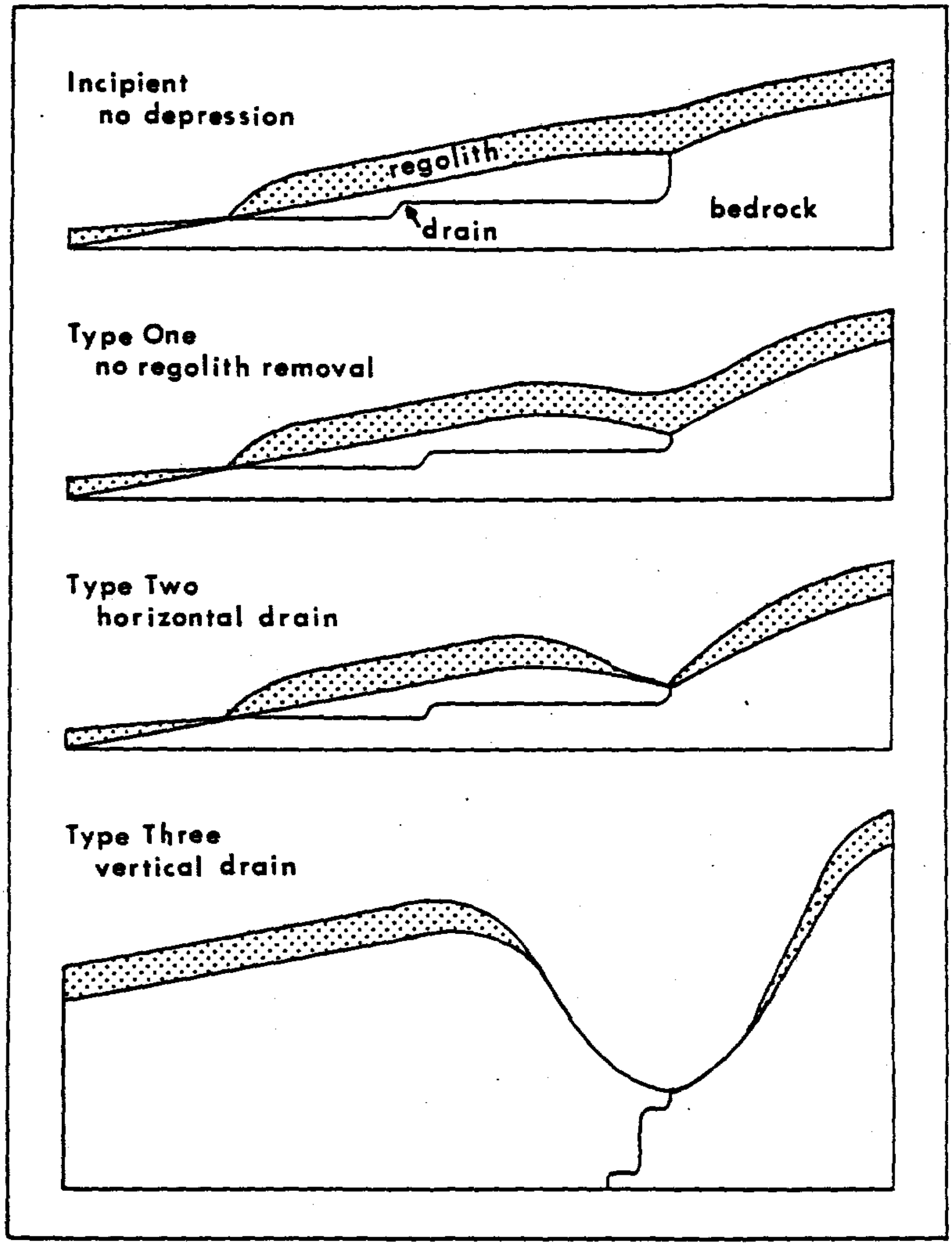

Figure 8. Types of sinkholes. See section F3a for discussion.

relatively short drains to discharge sediment into the effective transport environment of the larger conduit, and are more likely than other sinkholes to deepen rapidly, possibly to the point where they break through into the underlying conduit. A relatively minor factor in this process (which is believed to be responsible for the formation of karst windows in the region) may be some collapse of the roof of the underlying conduit in response to the deepening of the overlying sinkhole and enlargement of its drain.

Finally, it should be noted that in every instance of collapse at the surface in sinkholes known to the writer, the collapse has been due to the rapid subsidence of transport of regolith by infiltrating water within a type two or more commonly a type three sinkhole, and no collapse of bedrock is involved. The balance between water and regolith transport through the sinkhole drain suggests that such events should be common, but their occurrence has been greatly influenced by the practice of sinkhole filling discussed below. Regolith collapse outside of sinkholes (i.e., not in topographic depressions) is not uncommon as well. All such collapses the writer has examined were due to the failure of the roof of a shallow conduit developed at or above the regolith-bedrock interface.

F3b. Sinkhole Filling and Map Inadequacy

In some cases, type three sinkholes, which indicate the presence of a groundwater basin, can be identified rather easily on the topographic maps (Scale 1:24000; contour interval 3.0 or 6.1 m) of the region. The method used is to determine the minimum length necessary for the bottom of the sinkhole to be drained by a near horizontal conduit. If this length is greater than two or three hundred meters it is quite unlikely that such a horizontal sinkhole drain exists and the sinkhole is judged to be of type three. Unfortunately, the depth of sinkholes, especially the deeper ones of small area, is almost always several meters greater than the depth depicted on the map by topographic contours, since shadows and dense vegetation obscure their bottoms on aerial photographs. Deep sinkholes less than 50 m across are seldom shown at all on the topographic mpas. Many type three sinkholes can be identified as such only by field reconnaissance, therefore.

A second factor hinders the identification of the type three sinkholes, and hence groundwater basins, even after field reconnaissance. Deep sinkholes with steep walls provide convenient sites for rural waste disposal, often with the long-term goal of nearly filling them and rendering them suitable for pasture or even row crops. This effort by farmers has presumably been underway for much of the two centuries of agriculture in the region, with the result that many sinkholes that are actually type three now have a shallow saucer-shape more characteristic of type one or type two.

The topographic maps of the region do not accurately depict many of the other karst landforms which indicate the presence of a groundwater basin. Few of the streams in pocket valleys and karst windows are shown, probably because they are so short and hidden by vegetation and shadows. Many blind vallyes and paleovalleys are shown as normal surface valleys, especially when the reversed slope below swallets is gentle or short. Finally, swallets are too small to be termed landforms or to be shown even by accurate maps, although their presence is indicated in some blind valleys. Swallets along surface streams and in sinkholes (many sinkholes do not contain open swallets) can only be located in the field.

F4. Groundwater Basins and Wells

If the divisibility of the Inner Bluegrass Karst Region into groundwater basins and interbasin areas is valid, it should be reflected in the yield and water quality of wells and in the elevation and continuity of the potentiometric surface. Specifically, wells in groundwater basins would be expected to be more likely to have higher yields of meteoric water, due to the large and well integrated conduits present in the basins, than wells in interbasin areas where the subsurface conduits are smaller and not well integrated. The potentiometric surface in groundwater basins should be nearly flat and continuous, and up to 30 meters beneath the surface in topographically high areas. In interbasin areas the potentiometric surface would be expected to be shallow and exhibit apparent high gradients between nearby wells, reflecting its discontinuous nature. In topographically high areas, a rapid rise in the apparent potentiometric surface would be expected at the margins of basins.

As will be discussed in a later section, the zone of meteoric water beneath the potentiometric surface is believed to be of limited thickness in both basins and interbasin areas, and is underlain by a system of "non-meteoric water" of undesirable quality, containing high concentrations of dissolved ions and significant amounts of reduced sulfur. It would be expected that more wells in interbasin areas will have encountered this non-meteroic system, both because it is generally shallower and because fewer wells obtain an adequate yield of meteoric water in interbasin areas, causing them to be drilled deeper.

Correlations could not be made between the groundwater basins and interbasin areas of this study and the predicted yield maps of Hamilton (1950) and Faust (1977, plate 2) which were based on the influence of topography and stratigraphy and show no original data. The similar maps of Hall and Palmquist (1960d) and Palmquist and Hall (1960 b, c) also show no correlation with groundwater basins, and the original data presented are too sparse for interpretation. Only a very small portion of the Centerville quadrangle studied by Johnson and Thrailkill (1973) falls in the area of this study, and there are too few yield data on wells in the area of overlap to be useful.

Similarly, the two potentiometric surface maps available for areas in the region could not be used. The map by Faust (1977, plate 1) is at such a small scale (1:250000) and large contour interval (30 meters) that no comparison with the location of groundwater basins could be made, especially since no original data is shown. The map by McCann (1978, p. 33), while apparently consistent with the dye traces performed, is difficult to interpret in the absence of data values, and is in an area where only very scattered information on yield and water quality have been published (Hall and Palmquist, 1960 d).

The only portion of the area studied in which a substantial amount of yield, water quality, and potentiometric surface data is available is within the Georgetown quadrangle, as described below.

F4a. <u>Georgetown Quadrangle</u>

Information was assembled (Appendix 5) on 111 wells (in 67 of which water levels were reported) in the Georgetown Quadrangle from data in Hamilton (1950), Palmquist and Hall (1960 c), Mull (1968), and Thrailkill and Troester (1978). This area of about 100 km^2 is within the most intensively investigated portion of the Northern Fayette and Souther Scott counties study area. The density of well data ($1.1/km^2$) and potentiometric surface elevations

($0.7/km^2$) is greater for this area than for any other of comparable size in the Inner Bluegrass Karst Region, and although the quality of data is low (especially on yield and quality), it probably is about equal to that which could be obtained at present.

Figure 9 shows the location of all wells, dye introduction and detection points, groundwater basin outlines, and the location of the 28 "unsatisfactory" wells. Such wells are described variously as containing sulfur, salt, iron, gas, or as being dry (Appendix 5). Of the total 26 wells in groundwater basins, seven (27%) are unsatisfactory, as compared to 21 (25%) of the 85 total wells in interbasin areas. One of the basin unsatisfactory wells (number 63) is near the center of the Slacks Spring basin, while the remaining six cluster in the southern part of the same basin very near the position of major flow conduits inferred from dye introductions D10, D51a, and D56a (Figure 9). This suggests that the areas of higher yields and quality postulated for basins are quite narrow or non-existent.

Potentiometric surface elevations (for wells where data are available), potentiometric surface contours, and groundwater basin outlines are shown on Figure 10. The southern part of the Slack Spring Basin is quite well shown by the potentiometric surface contours, and the Royal Spring, Silver Springs, and Sharp Swallet basins are each indicated by one or two wells. Furthermore, the expected high gradients at basin margins are found in the Slacks Spring basin (between well numbers 59 and 62 and between 83 and 91), the Sharp Swallet basin (20 and 16), the Royal Spring basin (36 and 42), and the Silver Springs basin (110 and 108). These indicated gradients are as high as .05, which is inconsistent with a continuous potentiometric surface in a karst region under normal flow conditions. Finally, the irregular and locally steep potentiometric surface in the interbasin area between the Slacks Spring, Royal Spring, and Silver Springs basins is consistent with the earlier prediction, as is the high proportion of wells in which the potentiometric surface is within 5 m of the land surface (Appendix 5). The reentrant of the 250 m contour which encloses well number 78 suggests the presence of a small untraced groundwater basin discharging at a spring on Cane Run (Figure 10).

The relationship between the potentiometric surface and the Slacks Spring basin is complex. Elevations in six widely separated wells (59, 63, 69, 80, 83, and 101) in the central part of the basins are consistent with a gently sloping surface draining north to Sloanes Spring, whose estimated

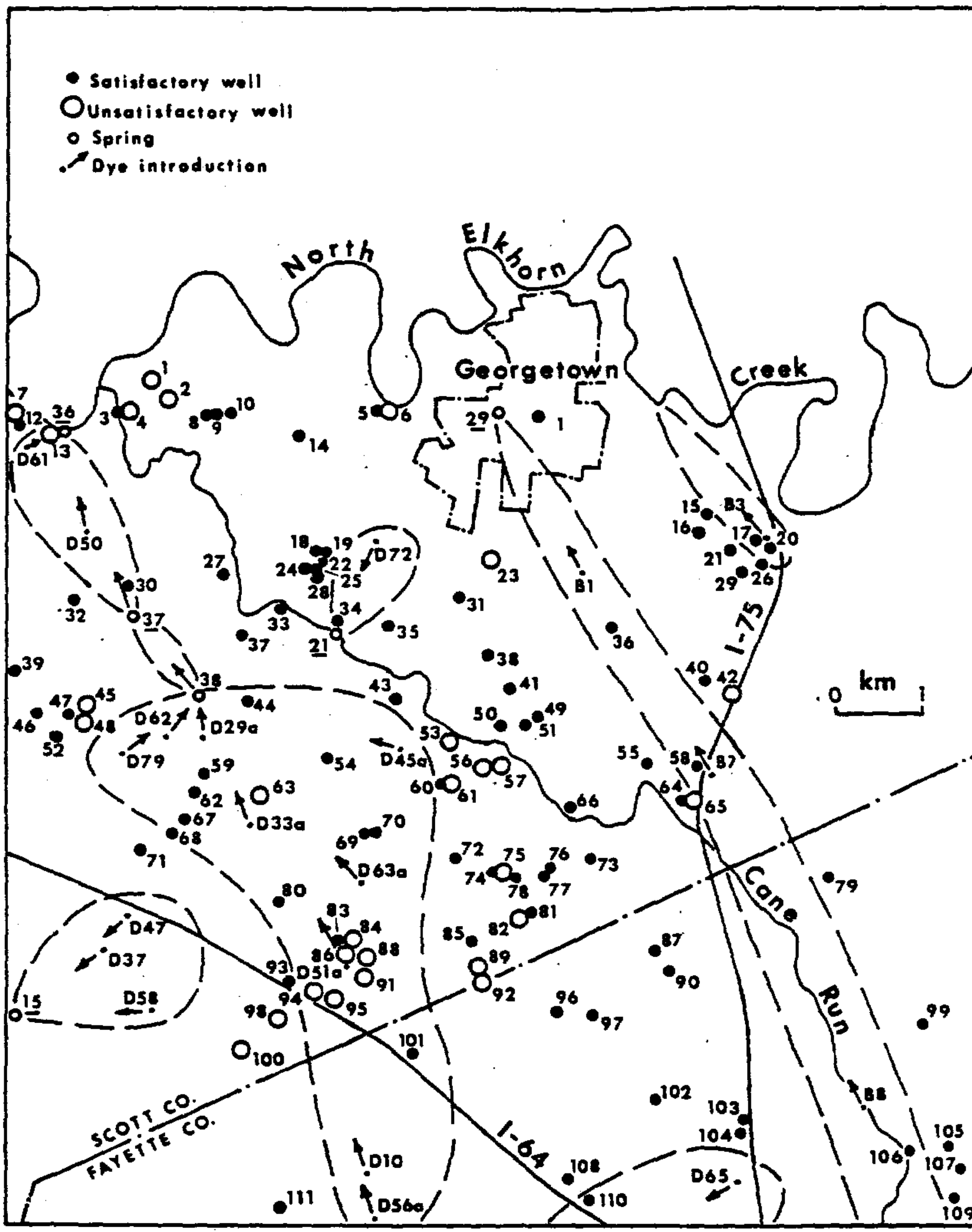

Figure 9. Map of Georgetown quadrangle showing satisfactory and unsatisfactory wells (Appendix 5), springs (Table 2), dye introductions (Appendix 1), and groundwater basins (dashed outlines). See section F4a for discussion.

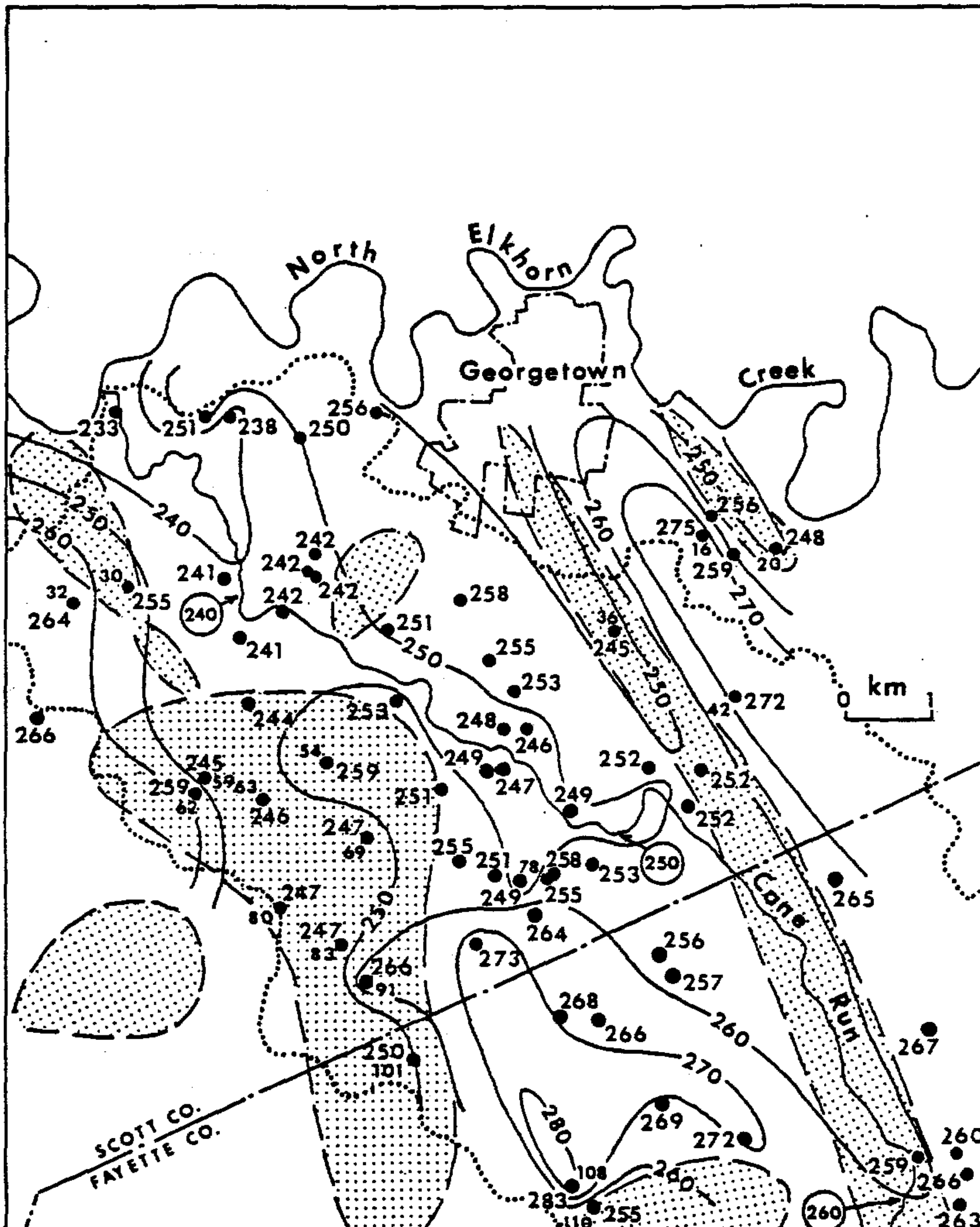

Figure 10. Map of Georgetown quadrangle showing wells with potentiometric surface elevations (large numbers) in meters, potentiometric surface contours (solid lines) and groundwater basins (dotted pattern). Numbers (Appendix 5) shown for wells discussed in section F4a. Circled numbers are elevations along Cane Run and dotted line is boundary (after Mull, 1968) of its surface drainage basin.

elevation (Appendix 1) of 247 m may be slightly high. To the north, however, this surface merges with the low area along Cane Run, and there is no evidence of the major flow line in Slacks Cave, which is well mapped and known to pass between wells 30 and 32, and the broad area above 250 m in the vicinity of well 54 does not suggest the trace from D45a (Figure 9).

The potentiometric surface low extending along Cane Run generally reflects the elevation of the stream (circled values on Figure 10), and most of these wells either have water levels within 5 m of the surface (Appendix 5) or are on high land quite close to the stream.

To summarize, no relationship between well yield or quality and position in a groundwater basin could be determined with the available data. There is, however, evidence that the expected configuration of the potentiometric surface in basins and interbasin areas does exist, except that the expected width of the basin on either side of some major flow conduits is not great enough to be detected by even rather closely spaced wells.

F5. Contaminant Transport

The tasks of determining the locations affected by actual or potential sources of contamination, and of identifying the source of contaminants detected, is a difficult matter in the Inner Bluegrass Karst Region and other karst areas. One of the principal goals of the present study, therefore, was to answer such questions, both for specific areas by dye tracing, and for the region in general by an understanding of the nature of its subsurface flow.

D5a. Destination of Contaminants

Within the areas studied, contaminants introduced into traced swallets, either directly or from streams whose flow is diverted underground, will be transported to the spring at which the trace was detected. Furthermore, contaminants introduced into other swallets, or which enter the meteoric suburface flow system in sinkholes, wells, and other points within the groundwater basins as outlined will probably also be transported to the major spring draining the basin. The location of springs, traced swallets, and the outline of groundwater basins are shown on Figures 2, 3, and 4.

Because subsurface flow in interbasin areas is believed to be generally downslope, the path of subsurface contaminants may be predicted on the basis of surface topography and drainage basins. Subsurface flow in such areas will often reappear at high-level springs (which may furnish the opportunity for contaminants to be monitored) and may be diverted underground for short distances where it follows shallow conduits. If such water enters a groundwater basin, it will generally enter the basin conduit system through a swallet and flow to the discharging spring. In a few cases flow in surface streams above major basin conduits has been found, as discussed earlier. It is possible that situations may exist in which conduit flow at two levels to different springs may exist (i.e., two groundwater basins overlapping vertically), but no evidence of this was observed, and the seemingly ubiqutous presence of interbasin areas between basins would make it quite unlikely.

A further complication in evaluating the destination of contaminants is that only a portion of the flow of a surface stream may be diverted underground by a swallet, with the remainder remaining on the surface. Although usually this surface flow will ultimately be diverted underground downstream by swallets in the same groundwater basin, this is not always the case. During low flows of Cane Run, contaminants introduced into its headwaters, which extend to the center of the city of Lexington, will probably be transported on the surface for several kilometers. The middle reach of the stream is within the Royal Spring basin, and low flow will be diverted underground through one or more swallets. At times of higher discharge, only a portion of the flow is captured by the swallets, with the remainder flowing on the surface into the downstream portion of Cane Run, which is in an interbasin area, to discharge into North Elkhorn Creek. Thus although the total volume of water sinking at swallets and flowing to Royal Spring is greater at higher discharge, the amount of contaminants from the upper reaches of Cane Run transported to the spring will be less.

F5b. Source of Detected Contaminants

Contaminants detected in a spring or the stream it feeds are derived from its groundwater basin or those portions of its catchment that extend into adjacent interbasin areas. Because the conduit system in the basin is dendritic, all of its flow will emerge at the spring, with the following exceptions in some cases. Some springs have multiple outlets within a few tens of meters of each other (some of which flow only during periods of high discharge), and for some springs outlets whose location is unknown apparently exist. These outlets probably discharge into the stream fed by the spring downstream from the spring.

Because of the dendritic flow system, contaminants from a single point-source within the catchment area of a spring will generally be greatly diluted before emerging at the spring. Conversely, non-point-source contaminants from a large area will be collected. It should be noted that this might create a hazard even in interbasin areas where, for example, dissolved pesticides from a field may be collected and discharged at a high-level spring used (as many are) as a livestock water supply.

As discussed earlier, a number of the springs of the region contain optical brighteners, often in such high concentrations that another dye tracing agent had to be used. It is presumed that this "background" optical brightener, which is a common additive to laundry detergents, is derived from septic tank effluent and sanitary sewer leaks. A study is now underway to attempt to relate background optical brightener concentrations to levels of colliform bacteria.

F5c. Well Contamination

The dendritic subsurface flow pattern in the groundwater basins and, although less integrated and on a smaller scale, in the interbasin areas, is fundamentally different from the dispersive flow pattern of granular aquifers. A major result of this is that contamination of a well from even a nearby point-source of contaminants is unlikely. Nearly all wells in the region are fed by small conduits draining inconspicuous recharges in the vicinity of the well (generally upslope in interbasin areas). Such conduits are "upstream tributaries" in the dendritic network and the quality of the water they carry is unaffected by contaminants in the larger conduits draining swallets. It is likely, therefore, that colliform contamination in wells in non-urbanized parts of the region is due to mainly non-point sources, such as livestock grazing areas.

A few wells in the region have encountered, either accidentally or deliberately (in the case of wells located to intersect a known stream in a cave), a major flow conduit in a groundwater basin. Although such wells will have larger than average yields, they will be subject to contamination from sources upstream in the dendritic system they tap.

F5d. Flow and Other Parameters

In addition to having a dendritic rather than a disperse flow pattern, subsurface flow in the Inner Bluegrass Karst Region differs from groundwater flow in granular aquifers in other important respects. Due to the large hydraulic conductivities, flow velocities are high even with low potential gradients, as indicated by the data from dye traces (Appendix 1). The lowest flow velocity consistent with any of the dye traces was .00043 m/s (37 m/day) for trace C6a, but velocity on the order of 1 km/day are very common. A study of the distribution of dye concentrations with time was conducted (Thrailkill, et. al., in preparation) which will present specific information on the time required for a contaminant to travel to and be present at Royal Spring and Russell Cave Spring. Data from the various qualitutive dye traces suggests, however, that the duration of a contaminant pulse at a spring from an instantaneous introduction is of the same order as the travel time to the spring.

Another major characteristic of the karst aquifer in the region is its low specific storage relative to unconfined granular aquifers, resulting in a rapid decline in the potentiometric surface as water is discharged from the system, and hence a rapid recession of springs following a period of high recharge. This may have the effect of creating isolated reservoirs of contaminated waters which may very slowly leak out into the major flow and/or be flushed out during a later episode of high recharge.

Lastly, little or no adsorption of contaminants would be expected in view of the large cross-sectional area of the flow conduits and the low adsorptive properties of calcite, the principal mineral composing the bedrock of the region. Some adsorption may take place on the organic particles and clays of the transported regolith which fills or coats portions of the conduits.

Overall, therefore, the transport of contaminants in groundwater basin conduits resembles such transport in surface streams more than that in granular aquifers. The most significant difference from surface stream transport may be the absence of sunlight, which precludes photosynthesis as a process for reducing the concentration of some contaminants.

F6. Geologic and Other Factors Influencing Subsurface Flow and Groundwater Basin Development

A major objective of this study was to evaluate the degree to which subsurface flow and the location of groundwater basins delineated by dye tracing during this study could be explained by geologic and other factors. Such an explanation would not only contribute substantially to an understanding of the nature of subsurface flow in the region, but would allow the prediction of flow directions and location of groundwater basins in portions of the region where dye tracing has not been done.

A particular emphasis was placed on the relevance to subsurface flow of the geological information contained on the U. S. Geological Survey geologic maps of the areas investigated (Allingham, 1972; Black, 1964, 1967; Cressman, 1964, 1967, 1972; Cressman and Harber, 1970; Kanizay and Cressman, 1967; MacQuown and Dobrovolny, 1968; Miller, 1967; and Pomeroy, 1968, 1970), inasmuch as similar large-scale (1:24000) maps are available for the entire Inner Bluegrass Karst Region.

Previous hydrogeologic investigations of the region have dealt mainly with the availability of subsurface water, and have reached varying conclusions as to the importance of various factors. Hamilton (1950) believed the argillaceous units in the Lexington Limestone was the most important control of solution development, and Mull (1968) considered them a major factor. Palmquist and Hall (1961), Hopkins (1966a), and Faust (1977), in the other hand, did not emphasize the role of lithology, and considered topography to be the major factor. Mull (1968) ascribed such an important role to the dip of the rocks that he presented his well data for the Georgetown Quadrangle on a structure contour map. Hamilton (1950), Palmquist and Hall (1961), Hopkins (1966a), and especially Faust (1977) believed joints and faults played a significant role in subsurface flow and solution development. The only previous work utilizing traced flow paths was by Jillson (1945), who emphasized the geomorphic development of the flow to Royal Spring and indicated indirectly that downdip flow was a factor in its development (Jillson, 1945, p. 25-27).

F6a. Lithology of Stratigraphic Units

Of the 39 major springs draining groundwater basins in the study area, two are interpreted as being perched on argillaceous units in the Lexington Limestone. In one the perching is observable and seemingly clear cut; Shawnee Hefer Spring in the Mercer County area flows from a number of hillside outlets over a distance of 60 meters along the outcrop of the Macedonia Bed. Although no dye introductions were detected at the springs, its groundwater basin probably lies to the southeast, updip from the spring. The interpretation is only slightly less certain for Spring Lake Spring in the Northern Fayette and Southern Scott Counties area, which emerges at about the stratigraphic position of the Cane Run Bed well above the level of major streams, and is downdip from its traced groundwater basin.

None of the other 37 major springs draining groundwater basins in the study area indicate control by stratigraphic units in the Lexington Limestone. It would seem reasonable that the few that emerge somewhat above the level of major surface streams (e.g., Gano and Steeles Springs) are perched on argillaceous or otherwise resistant beds, but such beds, if present (such as the Macedonia Bed at Gano Spring, see section D1g) are not indicated on the geologic maps or accompanying lithologic descriptions, and were not observed in the field.

The control of shallow subsurface flow in interbasin areas (including such areas within groundwater basins) by mapped or unmapped argillaceous limestones appears to be more common. Not infrequently, two or more high-level springs will emerge at the same stratigraphic level, and in the Sinkhole Plain paleovalley a number of such springs emerge at the top of the Macedonia Bed.

There may be occasional perching of surface streams for short distances on argillaceous units (e.g., the middle reaches of Cane Run on the Cane Run Bed and the stream in the Joyland Cave blind valley on the Brannon Member), but such instances are not obvious nor widespread.

Because of the general parallelism in the areas studied between bedding and the overall topographic surface, most of the major flow conduits and springs are in the lower exposed units of the Lexington Limestone, especially the Grier Limestone, but the stratigraphic position of springs emerging from this unit varies over more than 12 meters, and there is no evidence of lithologic control. Similarly, those smaller groundwater basins that approximately coincide with surface drainages have their margins beneath surface divides which are often underlain by higher argillaceous units such as the Millersburg Member and the Clays Ferry Formation. The numerous examples from both small and large basins which do not show this accord with topography, however, indicate lithologic variations in the Lexington Limestone are of little or no importance in controlling the development of major flow conduits or the location of groundwater basins. Subsurface flow in major conduits occurs beneath all seven of the argillaceous units mapped in the area (Table 1), as follows (with the location of an example in parentheses): Macedonia Bed (Burgin Springs basin); Cane Run Member (Royal Spring basin); Greendale Lentil (Silver Springs basin); Millersburg Member (Russell Cave Spring basin); and the lower part of the Clays Ferry Formation (Cove Springs basin).

F6b. Bedding Attitude

The parallelism between bedding and the overall topographic surface mentioned above also complicates the evaluation of the importance of the dip of the rocks in determining flow directions in groundwater basins. There is no evidence, however, of any useful relationship between flow directions as indicated by dye traces and the dip as shown by structure contours on the geologic maps. Although flow in some of the smaller basins is approximately downdip (e.g., Versailles Spring, Votah Spring, Jenning Spring basins), in others it is nearly updip (e.g., Cornett Spring, Cove Spring, Hartman Spring basins) or along strike (e.g., Distillery Spring, Duvall Cave, Gano Spring basins). Flow directions in the larger basins appear to be similarly unrelated to local dip. In the Lindsay Spring and Silver Springs basins, flow conduits cross mapped anticlines and synclines at right angles, and in the Russell Cave Spring basin the discharging spring and dye input points are on opposite limbs of an anticline that appears to represent the crest of the Cincinnati Arch.

Because of the problems associated with detailed structural mapping of stratigraphic units which often show rapid lateral changes in thickness and lithology, and whose exposures may be subject to slumping and rotation on hillslopes, the structure contours shown on the geologic maps may not accurately reflect local bedding attitude everywhere. If such local structure is ignored and the orientation of flow directions to the regional dip is examined, no more consistent relationship is found. In the Northern Fayette and Southern Scott Counties area, while flow in the Royal Spring, Slacks Spring, and Nance Spring basins is to the north-northwest and down the regional dip, flow in the adjacent Silver Springs and Lindsay Springs basins is to the southwest along regional strike. In the Mercer County area the regional dip is to the west, as is the general flow direction in basins draining to the Salt River (e.g., Big Spring and Eureka Spring basins). In basins draining to the Dix and Kentucky Rivers (e.g., Burgin Spring and Shawnee Run Spring basins), however, flow is generally to the east and hence up the regional dip.

F6c. Faults, Joints, Sinkhole Trends, and Similar Features

A number of steeply dipping or vertical planar structural features, including faults, mineralized veins, and joints, are shown on the geologic maps of the areas studied. In addition, linear trends of sinkholes are shown by topographic contours and others are visible on aerial photographs (Thrailkill, et. al., in preparation).

Four of the 39 major springs draining groundwater basins emerge at or within a few tens of meters of a mapped fault. In two of these, I-75 Spring and Nance Spring, the dye introduction points (only one for I-75 Spring) were along the fault or an apparent (but unmapped) extension, and the major flow conduit for the basin is probably along or very near the fault. In the Shawnee Run Spring basin, the spring is on the downthrown (about 2 m) side of a small fault which trends at nearly right angles to the lines of flow from dye introductions on the upthrown side. A more complex relationship exists in the Shawnee Copperhead Spring basin, where a major flow conduit intersects an unmapped fault and may follow it to its intersection with a mapped fault near which the discharging spring is located.

Dye introductions were made in swallets located on mapped faults in three other groundwater basins. In the Sharp Swallet basin, flow appears to follow the fault and the discharging spring is probably on an unmapped extension. In the Boggs Spring basin, however, the flow was away from the fault (part of the same system as the I-75 Spring basin fault) at a high angle to the spring located some distance away from its trace. Similarly, in the Silver Springs basin, flow from several swallets located along a series of parallel mapped faults is at right angles to their trend, as was flow from a swallet on the opposite side of the faults from the spring.

The Northern Fayette and Southern Scott Counties area is bounded on the southeast by the northeast-trending Lexington Fault System, a series of parallel faults with up to 150 m of mapped displacement. The single dye trace made to Bailey Spring, which lies on the southeast (downthrown) side of a major mapped fault in the system, was from a swallet on the northwest side of the fault. The line of the trace, which was so short and apparently represented such shallow flow that no groundwater basin was defined, crossed the fault at nearly right angles.

It was possible to examine the relationship of a flow conduit to an unmapped mineralized vein in a cave in the Shawnee Copperhead Spring basin. The conduit intersects the barite vein in several places at various angles and appears to be unaffected by its trend. In the Silver Springs basin the major flow conduit appears to cross a mapped barite vein at about a 45° angle.

No general relationship was evident between traced flow lines and joint directions, although in a few cases, as in the Silver Spring basin near the barite vein discussed avove, the orientations of flow lines and mapped joints are similar. It should be noted, however, that except in the few places where a conduit is accessible and has been mapped, the only indication of the orientation of flow line is the relative positions of the dye input and detection points.

Linear trends of sinkholes are not uncommon in the Inner Bluegrass Karst Region. Based on a sample, there are about 1000 such trends identifiable on topographic maps in the region (Thrailkill, et. al., in preparation), and hence approximately 120 in the area studied assuming uniform distribution. Most are less than one kilometer long and more trend between northwest and north than in any other direction. Faust (1977, plate 2, p. 16) gave the location of 40 such trends and stated that they were probably favorable places to obtain groundwater.

Alligned sinkholes are present along the mapped faults in the I-75 Spring, Boggs Spring, Sharp Swallet, Nance Spring, and Silver Springs basins discussed above. Traces from swallets on opposite ends of a linear trend in the Northwest Woodford County area showed that the trend extends from the Roaring Spring to the Pin Oak Spring basins. Investigations in the Royal Spring, Slacks Spring, Cornett Spring, and lower Roaring Spring basins strongly suggest that the major conduit in each of these basins follow sub-parallel linear sinkhole trends. Furthermore, the principal conduit in the adjacent Sharp Swallet and Nance Spring basins follows mapped faults (as discussed above) which are rougly parallel to these linear sinkhole trends. These relationships are shown in Table 3, where the basins are listed from west to east.

Basin	Orientation	Interval	Flow Direction
Roaring Spring	N 25 W		N to So. Elkhorn Cr.
		8 km	
Cornett Spring	N 10 W		S to So. Elkhorn Cr.
		2.5 km	
Nance Spring	N 15 W		N to No. Elkhorn Cr.
		2 km	
Slacks Spring	N 25 W		N to No. Elkhorn Cr.
		5 km	
Royal Spring	N 25 W		N to No. Elkhorn Cr.
		2 km	
Sharp Swallet	N 45 W		N to No. Elkhorn Cr.

Table 3. Sub-parallel groundwater basins

The alligned sinkholes, similarity of orientation, and occurrence of mapped faults in two of the basins suggests the existence of a fracture set of regional dimensions, with the possibility that the fracture may be regularly spaced at intervals of 2-3 km. This hypothesis would suggest an additional fracture between the Royal Springs and Slacks Springs basins and two between the Cornett Spring and Roaring Spring basins. The first interval was intensively investigated but no groundwater basin was discovered in this area, which is on the northeast side of the valley of Cane Run. The interval between the Cornett Spring and Roaring Spring basins has not yet been investigated.

Note that, except for the Roaring Springs basin (which has the least well defined sinkhole trend), the orientation of the hypothesized fractures varies rather smoothly from N 10 W in the west (Cornett Spring basin) to N 45 W in the east (Sharp Swallet basin). The pattern does not extend farther to the east, since the next major basin is the Vaughans Spring basin, whose flow appears to follow a very well developed line of sinkholes which trends N 20 E. Flow in all of the basins is down the regional dip to the northwest except in the Cornett Spring basin where flow is updip to the southeast.

The presence of major subsurface flow conduits beneath linear sinkhole trends was discovered early in the study, but the nature of the features responsible was unknown. They were initially referred to as diaclases (Thrailkill, et. al., in press), a term which includes major ("master") joints, a set of closely spaced joints, or an unmapped fault.

Late in the study, the opportunity arose to examine one of these features underground in the major downstream conduit of the Slacks Spring basin. The conduit which is nearly straight, is typically about 6 m wide and 5 m high. It is developed in the Grier Limestone Member and the thin, irregularly bedded limestone typical of this unit is exposed in the sides of the conduit. Individual beds are seldom thicker than 30 cm and generally cannot be traced laterally more than a few tens of meters. Visible joints can seldom be traced more than a meter or so vertically, and those parallel to the conduit seldom extend for more than ten meters.

Over most of the one kilometer accessible length of the conduit, the ceiling is the nearly flat underside of an unusually continuous tabular limestone bed, a lithology more characteristic of the Tanglewood Limestone Member. The trace of a joint, apparently little enlarged by solution, is visible in the ceiling in many places. This joint parallels the conduit and can be observed in several places to be continuous for at least 50 meters. The flat ceiling (often several meters wide) is due to collapse of weaker beds up to the more resistant and continuous bed, and is a common process in the nearly horizontal beds of the region.

Thus it is believed that allignment of sinkholes and localization of major conduits in the absence of faults is controlled by the presence of a joint which, unlike most of joints in the region, is continuous both horizontally and vertically (at least 30 meters in the one observed judging by the depth of the conduit beneath the surface). The presence of such a joint will promote the development of deep sinkhole drains near the surface, and hence type three sinkholes (as discussed earlier). At depth it will furnish a favorable path for initial conduit development if it trends at a small angle to the early potential gradient (as will be discussed below). Such conduits will more likely form in thin bedded limestones with closely spaced joints, and little enlargement of the joint in massive and horizontally extensive beds (such as forms the ceiling of the conduit as described above) would be expected with the exception of occasional near-vertical sinkhole drains.

This interpretation may explain the rather anomolous situation in the lower Vaughans Spring basin, where the path of the major conduit down flow from a karst window is along a linear trend of sinkholes, but then passes beneath North Elkhorn Creek to the spring on the opposite side. It is presumed that the conduit is developed along a fracture which has localized the sinkhole trend but is beneath a resistant bed at the creek, rising through it on the far bank at margin of the bed or at one of the few points it is penetrated by a solution opening. It would seem likely that the spring, which is on the inside of the meander loop, was once on the opposite (south) side of the creek, and that the creek channel has migrated lateraly on the resistant bed.

F6d. Topography

There appears to be no consistent correlation between groundwater basins and surface drainage basins. Several of the smaller groundwater basins (e.g., Baker Cave Spring, Humane Spring, Gano Spring, Santan Spring, and Tevis Spring basins) appear to at least approximately underlie surface drainage basins. In other small basins, however (e.g., Pin Oak Spring, Cove Spring, Hartman Spring, Sharp Swallet, and Elkhorn Spring) subsurface flow lines cross surface divides. All of the larger groundwater basins extend beneath surface divides. Examples include (with surface divide in parentheses): Big Spring basin (Salt River-Kentucky River), Nance Spring basin (North Elkhorn-South Elkhorn creeks), Silver Springs basin (Town Branch-Cane Run), and Russell Cave Spring basin (North Elkhorn Creek-Cane Run). In addition, in no instance were the boundaries of groundwater basins related to the divides of paleovalleys, such as the Lees Branch paleovalley in the Northeast Woodford County area or the Sinkhole Plain paleovalley in the Mercer County area. In contrast, the flow direction of the shallow subsurface flow in interbasin areas in believed to be generally accordant with surface drainage as discussed earlier.

Although the flow direction in groundwater basins appears to bear no consistent relationship to the details of present topography, there does seem to be a tendency for such flow to be toward the nearest major surface stream. In the Mercer County area, groundwater basins appear to be developed on either side of a line drawn midway between the Salt River to the west and

Herrington Lake (Dix River) and the Kentucky River to the east. Similarly, in the Northern Fayette and Souther Scott Counties area, groundwater basin flow is generally away from a line midway between South Elkhorn Creek and Town Branch on the southwest and North Elkhorn Creek to the north and east. These flow directions would correspond to the slope of the potentiometric surface of a regional aquifer (which does not now exist) discharging along these major streams.

F6e. Geomorphology

There have been easily interpreted changes in the landscape related to the development of underground drainage. The upper portions of a number of surface valleys have been converted into blind valleys and, in a few cases, paleovalleys have been created by the diversion underground of essentially all surface drainage. Similarly, in several of the caves of the region passages which are not now carrying subsurface flow are found a few meters above the active flow conduits, and there are high-level openings near a few of the major springs(e.g., Roaring Spring, Lindsay Spring) that probably represent abandoned conduits (although most of these are utilized during high flow). None of these higher-level conduits, however, indicate earlier flow directions or groundwater basin boundaries which are different from those now active.

Prior to the Mercer County area study (and one of the reasons that area was selected), it was hypothesized that the degree of groundwater basin development would be less near the margins of the region and in other areas where the Lexington Limestone has more recently lost its cover of the overlying argillaceous Clays Ferry Formation. Such a relationship, which was discussed briefly in Thrailkill, et. al. (in press), was not born out by the Mercer County area study, where well developed groundwater basins (e.g., Baker Cave Spring,and Cove Springs basins) are adjacent to and even beneath outcrops of the Clays Ferry Formation.

F6f. Conclusions and Utility of Geologic Maps

The preceding analysis indicates that no single factor or simple combination of factors appears to control the location of groundwater basins or direction of subsurface flow within them. The best predictor of general flow direction would seem to be proximity to a major surface stream, in that most of the flow in most of the basins in the areas investigated was generally toward such streams, probably in response to a potentiometric gradient in existence early in the development of the subsurface flow systems.

Groundwater basins will be found beneath deep sinkholes, blind valleys, and paleovalleys, but the lack of such landforms does not necessarily indicate the presence of interbasin areas. Where the trend of aligned deep sinkholes does not deviate from the direction of the early potentiometric gradient by a large angle, it is likely that major basin conduits are developed beneath such an alignment.

All of the above features are shown, with varying degrees of accuracy, on the topographic maps of the region. The principal information presented on geologic maps, the areal extent and lithologic nature of stratigraphic units in the Lexington Limestone, is of little or no utility in locating the boundaries of and flow directions within groundwater basins, nor does bedding attitude as shown by structure contours provide useful information. About the only features delineated on geologic maps (and not on topographic maps) which may be of interest are faults along which alligned sinkholes are not present, although no conduits were shown to follow such faults in the area studied. It is possible that there is a slight tendency for basins in which the flow is down the regional dip to be enlarged relative to those in which flow is updip, but no real evidence of this was seen during the study.

F7. Nature and Development of the Hydrogeologic System

The following discussion may be premature, inasmuch as no studies in the region of important topics such as water budget or carbonate geochemistry have yet been completed. The relationships established during the present study, however, provide a framework for an explanation of the nature and development of the hydrogeology of the system which is sufficiently different from the views of earlier workers to justify its presentation.

The ideas which will be presented are based on arguments which are rather highly deductive. The only portion of the subsurface system which can be directly observed in any detail are conduits which are large enough to enter and are not completely water filled. Although consistent with observations which have been made during the study, the properties of, and

and processes occurring within, the smaller conduits must mainly be deduced from physical principles.

The differences between the hydrogeology of the region and that of areas underlain by granular material are so substantial that virtually the only feature the two systems have in common is the presence, flow, and availabilty to wells of water beneath the surface. Because a fundamental starting point for the description of the hydrogeology of granular aquifers and the overlying vadose and regolith zones is that the type of flow is such that Darcy's Law is followed, an examination of the types of subsurface flow in the Inner Bluegrass Karst Region is appropriate.

F7a. Types of Flow

Subsurface flow in an area underlain by granular material is largely through pores of such small diameter that the flow velocity is linearly related to the potential gradient by the hydraulic conductivity, a relationship described by Darcy's Law. In addition, flow in small planar fractures (e.g., joints and bedding surfaces) will also obey this relationship if the width of the fracture is sufficiently small. The term capillary size will be used here, although capillary effects are pertinent only in unsaturated flow. If the pores (and fractures) are not saturated with water, the flow will be termed unsaturated intergranular flow (and the degree of saturation is an added parameter in flow relationship), otherwise the flow will be termed saturated intergranular flow. Although other types of flow may occur, as in large soil fractures and in areas of high potential gradient near pumping wells, they may usually be safely neglected in describing the hydrogeologic system. The body of saturated granular material at depth in which saturated intergranular flow occurs, and in which the water pressure is greater than one atmosphere, is considered the aquifer (and its contents groundwater) if its hydraulic conductivity is high enough for water to be yielded to wells. Above the potentiometric surface (termed the water table if the aquifer is unconfined), at which the pressure is atmospheric, most of the flow is unsaturated intergranular flow, although a region of saturated intergranular flow, (lower portion of the capillary fringe) is usually present just above the potentiometric surface in the vadose zone and, locally and temporarily, in portions of the regolith as a result of high recharge.

In contrast, subsurface meteroic water in the Inner Bluegrass Karst Region is transported by six different types of flow, all of which are significant in describing the nature and development of the hydrogeologic system. In the regolith, flow is similar to that in the regolith overlying granular material, and water is transported largely by unsaturated intergranular flow, with areas of saturated intergranular flow beneath ponds and surface streams as well as elsewhere following heavy rains or snow melt. Unlike many areas of granular rocks with appreciable hydraulic conductivity, however, a zone of saturated intergranular flow is often present above the regolith-bedrock interface due to the very low hydraulic conductivity of the bedrock if no conduits are developed. In addition one or more of the four types of conduit flows discussed below may occur in the regolith (especially its lower part) in conduits excavated by piping and other non-solution processes.

Flow in the bedrock outside of conduits will be by saturated intergranular flow as well. Although this is overwhelmingly the largest region in the subsurface, intergranular hydraulic conductivities in the bedrock are so low that this flow is of no interest on a short time scale as a source of water to wells nor on an intermediate time scale of a few weeks to a few years in considering the water budget of the region. As will be discussed, however, such flow is important on a long (i.e., geological) time scale in understanding the development of the hydrogeologic system of the region. Note that the two types of intergranular flow include flow along narrow fractures, as well as that between grains.

The other four types of flow are in conduits, solutionally enlarged openings larger than the capillary size openings so far discussed. Although many conduits are tubes with rather regular cross-sections which change little along the length of the conduit, the term will also be applied to all large openings in the rock regardless of their shape.

Pipe flow occurs when the conduit is completely filled with water and (since there are no capillary effects and the venturi effect of high velocities is neglegible), the pressure is greater than atmospheric. The other types of conduit flow are unsaturated (i.e., the conduit contains both water and air). In bedrock channel flow, flow is on bedrock beneath a free surface, and hence the width, depth, and gradient are fixed for a given discharge except for solution and abrasion of the bedrock on a long time scale. Gravity flow differs from bedrock channel flow in having a very high gradient, lack of a well defined cross-sectional area, and poorly defined contact (or none in the case of water falling free) with the bedrock, which precludes the application of open channel flow relationships (e.g., Chezy-Manning) used for other types of unsaturated conduit flow. Finally, equilibrium channel flow is similar to bedrock channel flow (and is describable by open channel flow relationships) except that the bottom and sides of the channel are largely on sediment, mainly transported regolith and bedrock fragments, and its width, depth, and gradients on a long and possibly intermediate time scale are determined by an equilibrium between water and sediment transport. Such flow has been extensively discussed (under a variety of names) by many authors for surface streams (e.g., Leopold, et. al., 1964; Hammer and MacKichan, 1981).

Although other types of subsurface flow may occur in the region, such as in saturated or unsaturated conduits in areas of ponding or in saturated conduits partly filled with sediment, it may be assumed, at least initially, that such flow may adequately be described as one of the types described above. The properties of the six types of flow considered are summarized in Table 4.

F7b. The Non-Meteoric System

Before proceeding further with a discussion of the nature and development of the subsurface meteoric water flow system, some mention of what will be termed the non-meteoric system is in order. As discussed earlier in the section on water supply, many wells drilled in the region encounter water of unsatisfactory quality, in some cases at depths of less than 25 m (Appendix 6). This water is variously characterized as containing sulfur, salt, iron, etc., and may be present in appreciable quantities in some wells.

Although little is known of this subsurface water, several observations can be made. First, at least some of the water is in conduits (and presumably pipe flow at these depths), inasmuch as the intergranular hydraulic conductivity is too low to transmit the amounts of water that have been encountered. Second, the chemistry of the water indicates that it is isolated from the meteoric water system. Third, the absence of such water in many deep dry holes and underground quarries suggests that this system does not completely permeate the bedrock. Fourth, the apparent difference in chemistry of this water suggests that it may be in small, relatively isolated bodies, and that a continuous system does not exist. Finally, the fact that some wells

Type of Flow	Saturated or Unsaturated	Type of Opening	Pressure rel.to atm.	Predominant Flow Mode	Potential-Velocity Relationships
Saturated intergranular flow	Saturated	Capillary	Greater (occ. about equal or less)	laminar	Darcy
Unsaturated intergranular flow	Unsaturated	Capillary	Less	laminar	Darcy (modified)
Gravity flow	Unsaturated	Conduit	About equal	turbulent	Gravitational acceleration vertical film, etc.
Pipe flow	Unsaturated	Conduit	Greater	turbulent	Turbulent pipe flow
Bedrock channel flow	Unsaturated	Conduit	About equal	turbulent	Chezy-Manning. etc.
Equilibrium channel flow	Unsaturated	Conduit	About equal	turbulent	Chezy-Manning, Leopold, etc.

Table 4. Types of Subsurface flow in the Inner Bluegrass Karst Region

(e.g., number 61, Appendix 6) which initially yield water of unsatisfactory quality later produce meteoric water, suggests that pressure communication between the non-meteoric and meteoric systems may exist, and continued pumping of the former allows the latter to invade the conduits and flush them out. Alternatively, these cases may be explained by the well initially producing from both systems exhaust the non-meteoric system, which would support the suggestion that these are actually a series of isolated systems.

F7c. Conduit Initiation

Virtually by definition, the flow in bedrock prior to conduit development is by saturated intergranular flow, and such flow is now occurring in bedrock where conduits are not present. An examination of the transition from intergranular to conduit flow would thus seem to be an essential part of the development of the flow system, but as the following will show, no very satisfactory conclusion can be reached regarding this phase of the hydrogeologic history of the region.

The principal mechanism responsible for the initiation of conduits is solution of the mineral calcite, the principal constituent of limestones, and although various attempts have been made to quantify the relationships between solution and flow (e.g., White, 1977), much work remains in this area. It is evident, however, that conversion of an intergranular flow path to a conduit flow path requires the passage of large amounts of water simply to remove the solution products, regardless of the details of the solution kinetics or degree of chemical undersaturation of the water as it enters the flow path. Assuming a high and constant carbon dioxide partial pressure, no dissolved calcite in the water as it enters the flow path, and complete saturation with respect to calcite as it leaves it (all unrealistically generous specifications), a volume of water at least 1000 times the volume of the initial conduit (neglecting the volume of the intergranular flow path) is needed during the period of intergranular flow.

Assuming a potential gradient of .01 (based on the region's topography), a flow path length of 5 km, and a minimum time for water to traverse the flow path of 10 years (thus providing the above volume in 10,000 years), an application of Darcy's Law yields a minimum hydraulic conductivity along the flow line of a little more than 10^{-5} m/s.

Intergranular hydraulic conductivities of the limestones and thin shales of the Lexington Limestones are low. MacQuown (1967, p. 68), gives a determination equivalent to about 10^{-9} m/s for a specimen of the Curdsville Member, which is lithologically similar to the Tanglewood Limestone Member. Freeze and Cherry (1979, p. 29) indicate that a hydraulic conductivity of 10^{-9} m/s is about the lower limit for limestone, and hence this probably represents intergranular, as opposed to fracture, hydraulic conductivity.

The actual flow velocity along a flow path will be inversely related to the bulk velocity (suggested by the hydraulic conductivity) by the void ratio, assuming the flow path is straight. A void ratio of 10^{-3}, and a degree of tortuousness of the flow path such that is is ten times the straight line distance, yields a flow velocity of 10^{-7} m/s, two orders of magnitude too low for conduit initiation under the conditions assumed.

Because the Lexington Limestone is thin-bedded and the individual beds are jointed, pre-conduit flow along bedding and joint surface, which will collectively be called fractures, would seem likely. Such flow in a system of narrow fractures, (assuming certain conditions of their interconnection and spacing are met) will obey Darcy's Law and is here considered saturated intergranular flow, even though the flow paths are not between grains.

MacQuown (1967, p. 47) found the average spacing of bedding surfaces to be .05 m and the average joint spacing to be .24 m in the Curdsville Member, which yields a value of 24.2 fractures/m^2. Assuming a width of 0.1 mm (10^{-4}m) for a fracture which has not been solutionally widened, a hydraulic conductivity of about 10^{-11} m/s is obtained using methods described in Freeze and Cherry (1979, p. 74), and the void ratio (assuming all fractures are parallel to flow) is about 2.5×10^{-3}. Even if no path lengthening due to tortuousity is considered, a flow velocity within a fracture of 4×10^{-9} results, one and one-half orders of magnitude less than that of an intergranular path.

Although this admittedly crude analysis suggests that intergranular flow paths should be favored over fracture flow paths during the pre-conduit flow stage, the reverse is probably true, since small conduits observed in outcrop are usually, but not invariably, localized along a joing or bedding surface. Thus there may be errors and inconsistencies in the assumptions, most notably in the specification of fracture width. Since hydraulic conductivity along a fracture is directly related to the third power of the fracture width (Freeze and Cherry, 1979, p. 74), if the width is 1 mm (10^{-3}) rather than 0.1 mm, the hydraulic conductivity is increased by 3 orders of magnitude, favoring fracture paths over intergranular paths. Such a width for non-solutionally widened fractures at depth seems too great (0.1 mm is probably too generous), but it is likely that some solutional widening (and even conduit development) has occured in at least some fractures prior to the initial entry of meteoric water. Openings large enough to transmit the non-meteoric system discussed earlier are certainly present in some places in the rock.

The apparent near-comparable efficiency of intergranular paths suggests that pre-conduit flow along such paths cannot be ignored, however. If a steep potential gradient were present at an angle to bedding where no joints were present, enlargement of intergranular paths parallel to the gradient would be expected. Such paths would probably even cross shale interbeds up to several millimeters thick (which probably includes most such interbeds in the Lexington Limestone) inasmuch as the shales generally contain more than 50% calcite (and dolomite) and less than 25% clay minerals (Fisher, 1968, p. 780), and hence even their vertical hydraulic conductivity may be comparable to the hydraulic conductivity of the limestones. Conduit development in such shales would be inhibited by the accumulation of insoluble residue, however.

Ewers and Quinlan (1981) have presented the most persuasive explanation for the initial development of conduits from saturated intergranular flow along a fracture. Ewer's (1981) experiments (utilizing salt and plaster) indicates conduit development begins at the input point and extends down the flow as a complexly-branching dendritic pattern of small conduits. Because potential loss in the conduits is much less than in the intergranular flow region, the steepest potential gradient is between the outlet and the end of the conduit nearest the outlet resulting in increased flow and accelerated conduit growth along this line. Once the first conduit reaches the outlet, potential falls in all the conduits and flow within and growth of the other conduits in the dendritic pattern virtually ceases. If dendritic patterns of conduits are growing from other input points, a steep potential gradient develops in the intergranular flow region between these conduits and those of the patter which first reached the outlet, causing conduits from the other input points to grow toward, and eventually join, conduits in the pattern that first reached the outlet. Thus the first type of dendritic pattern (branching downflow) is converted to the more familiar second type (branching upstream).

F7d. Stages in Conduit Growth

Further solutional (and abrasion) enlargement of the conduits and integration of the conduit system has led to the present hydrogeologic system of the region. During this enlargement and integration, individual conduits have passed through a number of stages which are significant. The transition to the first stage occurs when the cross-sectional area of a conduit becomes sufficiently large, and the flow velocities (due to integration of the conduit system) sufficiently high, for the flow to become pipe flow, and hence no longer described by Darcy's Law. Prior to this transition, the flow would be saturated (usually) intergranular flow even though it was in the embryo conduits described in the preceding section. Because both the plan and cross-section of the conduits are probably quite irregular, the transition to the first stage probably occurs well before the flow becomes turbulent.

The transition to the _second stage_ occurs when conduit size throughout its length is great enough for sediment (both regolith and the insoluble residue from the solutional enlargement of the conduits) to be transported through the system. The _third stage_ is reached when the size of the conduit and the flow velocities are sufficiently high for conduits on bedding surfaces above thin shales or otherwise resistant beds to erode through to the underlying less resistant limestone. The conduit size and flow velocity necessary is obviously a formation of the extent, thickness, and degree of resistance of the underlying bed.

It seems unlikely that significant sediment transport can occur unless the flow is turbulent, and conduits which are able to erode shales (probably mainly by solution, inasmuch as the "shales" are dominantly carbonates, as discussed earlier) must be able to transport the insoluble residue out of the conduit. Thus the three stages would seem to be sequential. There is another transition that occurs at some point during the enlargement of a conduit and integration of the system whose position in the sequence may vary, although it probably occurs most often during the second stage. This transition occurs when the size of the conduits and integration of the system reaches the point where the amount of water being supplied to the conduit is insufficient to fill it, at least during times of low recharge, and the flow becomes unsaturated, either _bedrock channel flow_, if the gradient is low, _gravity flow_, if the gradient is high (most common in a third stage conduit), or _equilibrium channel flow_ in larger and deeper conduits.

Where the conduit serves as a sinkhole drain, this classification corresponds to the classification of sinkhole types outlined earlier, in that incipient and type one sinkholes are drained by first stage conduits, type two sinkholes by second stage conduits, and type three sinkholes by third stage conduits.

As stated earlier, geochemical studies of the ability of recharging meteoric water to accomplish the conduit enlargement have not yet been completed in the region. A considerable body of literature exists on this question based on studies in other areas, however, (e.g., Thrailkill and Robl, 1981), and it is believed that this model of conduit initiation and development is consistent with the geochemistry.

F7e. Groundwater Basins, Interbasin Areas, and the Aquifer

Groundwater basins have been idnetified as areas within which dye tracing has indicated that the subsurface conduit system appears to be deep, extensive, and well integrated, while there is no evidence that the subsurface conduit system in interbasin areas has any of these characteristics. In groundwater basins, at least the major flow of meteoric water infiltrating the surface descends steeply through stage three conduits from stream swallets or as type three sinkhole drains.

In two of the groundwater basins indentfied (Shawnee Hefer and Spring Lake Spring basins), the major basin conduits are believed to be perched on a resistant bed, and thus have not reached the third stage of development relative to this bed (although third stage conduits are probably developed through thinner resistant beds above it).

In the remaining 36 groundwater basins, flow within them appears to be in large, nearly horizontal conduits, whose elevation is unrelated to lithology. Where major conduits can be entered and examined, they consist of open passages traversed by a stream flowing over sediment, with accessibility terminating both upstream and downstream when the conduit becomes completly filled with water. The nearly horizontal gradient of these major conduits is believed to be controlled by the equilibrium flow occurring in the unsaturated portions of the major conduits.

As discussed earlier, the width of the zone of near horizontal flow at depth in groundwater basins is uncertain. Although potentiometric surface elevations in the middle Slacks Spring basin suggests that it may be extensive, other evidence would seem to indicate that conduit development between major flow lines within the basin is minor or absent, and that the basin flow is largely through a single conduit or, in a few cases, conduits parallel to and very near the major conduit. Such evidence includes the well data from the lower Slacks Spring basin and other basins in the Georgetown Quadrangle, the fact that most of the springs either have a single outlet or multiple outlets very close to each other, and that impoundment of springs has not led to their abandoment and a major diversion of flow as the potential is increased.

Subsurface flow within the groundwater basins (neglecting the saturated and unsaturated intergranular flow in the regolith and saturated intergranular flow in the bedrock outside of conduits) is thus different in different parts of the basin. Water entering the basin from stream swallets and type three sinkhole drains initially descends steeply by gravity flow and short reaches of bedrock channel flow to the floor of the basin. It then is transported to the discharging spring mainly by equilibrium channel flow and pipe flow, although reaches of low gradient bedrock channel flow several hundred meters long have been observed in the upstream portion of smaller conduits.

Although it is rather easy to explain the near horizontal flow in the groundwater basins as being due to equilibrium channel flow in at least major portions of the larger conduits, it should be noted that other, and unknown, factors promoting this horizontal flow may be operating. By its very nature equilibrium channel flow requires that large amounts of sediment are being transported in the subsurface. While this is certainly true in the Inner Bluegrass Karst Region, it may not be in other karst areas where near-horizontal flow also occurs. This equilibrium flow explanation is not, therefore, necessarily a general explanation of the causes of shallow versus deep phreatic flow which has been extensively debated in the literature (e.g, Thrailkill, 1968).

In hydrogeologic systems, an aquifer is considered to be a body of rock which contains water which is available to wells in useful quantities and which is under a pressure greater than atmospheric. In addition, the water should be of usable quality. The term has been avoided so far in this report because the nature of the subsurface flow system in the region is so different from that in granular materials that the term is essentially meaningless unless carefully characterized. Similarly, since the term groundwater is best reserved for water in the aquifer, ther term subsurface water has been employed.

In the Inner Bluegrass Karst Region, therefore, the aquifer consists only of rock in which conduits are developed (since intergranualr flow does not satisfy the yield criteron) which contain meteoric water (the non-meteoric system fails the quality criteron) at greater than one atmosphere pressure. Because shallow bedrock channel flow and equilibrium channel flow, as well as gravity flow, is at atmospheric pressure, only rock with conduits with pipe flow and the deeper water-filled portions of larger conduits in which bedrock channel flow and equilibrium channel flow occurs are included.

Within groundwater basins, the potentiometric surface is represented by the water surface in the larger conduits in which equilibrium channel flow is occurring. Adjacent conduits below this level are completely water filled if they are below this level, with the water pressure determined by the depth below the potentiometric surface. Flow in other conduits which are partly above this level will be mainly by bedrock channel flow, with equilibrium channel flow in those carrying large amounts of sediment from the surface. Well data from the middle Slacks Spring basin shows that at least in one basin the communication between these various conduits is sufficient to produce the expected nearly flat potentiometric surface over a wide area.

It should be noted that fairly high gradient bedrock channel flow occurs in many places, and at many elevations, in the groundwater basins. Since the gradient is high, the flow is rapid and shallow. This water was excluded from the aquifer in the above definition because it is essentially at atmospheric pressure and, since it is unlikely that the surface of such flows is reflected in the surface of nearby unsaturated flows or the pressure in pipe flow conduits, it is meaningless as a potentiometric surface.

In the smaller conduits in the interbasin areas, pipe flow and occasionally large channel flows may be encountered near the surface, and a consistent potentiometric surface may be definable over a small area. Along major streams, larger flows beneath a more continuous potentiometric surface at or just above the stream level would be expected. The margins of groundwater basins in topographically high areas are probably so steep that no aquifer exists.

Thus the Inner Bluegrass Karst Aquifer is discontinuous on two scales. Since it exists only where conduits are developed, it can be tapped by only a fraction of the wells that are drilled. In addition, since it can be defined only when pipe flow and low gradient channel flow are occurring, it may be characterized as being extensive in groundwater basins and along major surface streams, discontinuous and local in topographically high portions of interbasin areas, and may be absent at basin boundaries.

F7f. Influence of Human Activities

Some mention should be made of the effects of underground flow in the region as a result of human activities. The widespread practice of filling sinkholes mentioned earlier has probably decreased subsurface flow, since precipitation that formerly entered the subsurface rapidly through swallets in deep sinkholes is now retained in the regolith (and occasionally in ponds established in sinkholes) and evapotranspired. On the other hand, surface runoff into small streams and into swallets which divert their flow underground, has been increased by land clearing and urbanization. Although the net effect (to either increase or decrease recharge) may have been substantial, it cannot be evaluated with the present data. Because of the high hydraulic conductivity and low specific storage of the aquifer, however, such changes in recharge rate have a small effect relative to what would be expected in a granular aquifer.

Human activities have also modified the flow in conduits by causing subsurface sedimentation. The impoundment of major springs such as Russell Cave and Royal Springs has apparently produced extensive deposition in the downstream portion of the main conduit, and it is likely that the series of low dams which have been constructed on North and South Elkhorn Creeks has had a similar effect on some of the springs flowing into these streams. In addition, there are extensive fills of transported regolith in several of the accessible conduits in the region. In some cases these are in upper level conduits (mainly sinkhole drains) in which the water transport is by bedrock channel flow and gravity flow. Although some sediment would be expected to be transported through such conduits (and equilibrium channel flow might develop locally), the observed fill is far in excess of the amount expected and does not appear to be transported by even the highest recharge events. Similarly, the accessible portions of the major conduit in the Slacks Spring basin (whose spring is not impounded) contain large amounts of transported regolith on either side of the active equilibrium channel flow, and dates scratched into the fill indicate that much of it is not inundated or transported during high flows in the conduit. It is believed, therefore, that much of this "excess" sediment may have been introduced into the subsurface as a result of initial land clearing operations, probably in the early part of the 19th century.

Finally, it may be noted that groundwater basins exist within parts of the city of Lexington, as evidenced by the presence of major springs, deep sinkholes, karst windows, and blind valleys. No dye tracing has yet been attempted within this heavily urbanized area, however, due to the difficulty of clearly distinguishing natural subsurface flow from that in storm drains.

F8. Groundwater Availability

Other than a comparison of potentiometric surface data from wells with dye tracing information in the Northeast Woodford County area (McCann, 1978), and the earlier discussion of published well inventory data in the Georgetown Quadrangle, no systematic investigation of well success, yield, or quality has yet been undertaken in the study of the region. Considerable information on subsurface flow has been acquired by other methods, however, and the following comments on the siting, drilling, and outcome of wells drilled for water supply is both possible and appropriate.

Wells drilled within a few hundred meters of a major surface stream (e.g., North Elkhorn Creek, Salt River) may have a probability of as much as 50% of intersecting waterfilled conduits in the aquifer, which is probably two or three meters thick in such areas. The elevation of the potentiometric surface probably ranges from that of the stream surface to a meter or two higher. Groundwater in wells less than a hundred meters from the surface stream may partly or entirely derived from surface flow in the stream which has been diverted underground upstream. Wells drilled more than five meters below the potentiometric surface are more likely to intersect the poor quality non-meteoric water system than to find adequate supplies of groundwater. In a few areas along major streams, aquifers (which have not been considered in this report) may be developed in alluvum if it is unusually thick.

In topographically high areas away from major streams, a determination should be made as to whether the site is within a groundwater basin or in an interbasin area. In interbasin areas, groundwater (if an aquifer exists at the site) will be most likely to be found at or only a meter or two below the regolith-bedrock interface, and any water deeper than about five meters below the surface will probably be part of the non-meteoric system. The aquifer is likely to be less than one meter thick and the probability of encountering a conduit within it which is large enough to furnish a satisfactory yield may be less than 25%. Because of the correspondence between subsurface flow and topography in interbasin areas, wells will have a better chance of tapping a thick aquifer if they are sited in valley bottoms, sinkholes, down slope from shallow sinkholes or more level areas, and along sinkhole allignments which trend down slope. The recharge area will generally be upslope from the well and no concordance of the potentiometric surface (represented by the water level in wells which tap the aquifer) between wells more than a few hundred meters apart would be expected.

If the site is within a groundwater basin, either one described in this report or whose existence is inferred by the presence of high capacity swallets, deep sinkholes, or other features discussed earlier, substantial yields of groundwater may be obtainable. The elevation of the potentiometric surface beneath the site can be estimated by assuming its gradient to be about .005 toward the draining spring (if its location is known) or toward the nearest point on a major surface stream. An aquifer thickness of two or three meters beneath the potentiometric surface would be expected, and water encountered more than five meters beneath the potentiometric surface is likely to be of poor quality. It is possible that perched aquifers of limited extent may exist within the basin. Although some of the water in the main aquifer may have been derived from recharge several kilometers distant, most wells probably produce water that has infiltrated the surface within a distance of a few hundred meters (not necessarily up slope).

In many groundwater basins, much of the area within its outline has the surface characteristics of an interbasin area, and may also be similar in terms of aquifer development. Although deep flows of meteoric water are known to occur beneath such areas in a few places (e.g., Lindsay Spring basin), if water of unsatisfactory quality is encountered, the probabilities of obtaining groundwater at greater depths is believed to be too small to justify deepening the well. Very little information (some of it apparently conflicting) is available either on the extent of the aquifer (as indicated by accordance of water levels in adjacent wells) or the density of conduits on either side of major flow conduits which have been traced or which are in ferred from surface karst features, and little is usually known about the path of such conduits other than the location of their upstream end. It is probably worthwhile, therefore, to attempt to site a well as close to the most probable location of a major conduit and/or in areas where subsidiary conduits in communication with it are most likely to be present. Such sites include the bottoms of deep sinkholes, along a line between the bottoms of deep sinkholes (including allignments of several sinkholes) especially when the trend is toward the discharging spring or major stream, and along a line between a swallet or deep sinkhole and the discharging spring. In contrast to interbasin areas, lcoal topographic features of modest relief are probably of little importance.

It is likely that conduit development within and above the aquifer in those portions of groundwater basins that lie beneath more than ten meters of Clays Ferry Formation and possibly the Millersburg Member is less than elsewhere. In interbasin areas, both the extent of the shallow aquifer and the number and size of conduits are believed to be small in these units. In groundwater basins drained by springs located above the level of major streams, it is unlikely that groundwater will be encountered below the elevation of the spring inasmuch as such basins are probably perched on beds which are apparently resistant to penetration by third stage conduits. For the same reason, groundwater will probably be absent in interbasin areas below the elevation of high-level springs which appear to be stratigraphically controlled. Otherwise, however, the presence of argillaceous units is believed to exert little or no control over groundwater in the region.

Two other observations may be worth noting. First, there will tend to be an inverse relationship between yield and the occurrence of turbidity in wells, in that the higher yielding wells have penetrated larger conduits which generally have a direct communication with swallets and other points of high recharge from the surface. Second, flows encountered above the potentiometric surface (and hence not groundwater as defined) may furnish satisfactory yields in some cases (and probably do so in many wells in the region). Unlike pipe flow in the aquifer, such water will generally not rise in the well above the point where such gravity or bedrock channel flows are encountered. If the depth of the well below this point is sufficient, however, enough water may accumulate and be stored in the well to provide a small yield. Such vadose zone flows, however, are likely to cease or diminish substantially during periods of low recharge.

The above comments are based on information acquired during a study of only a portion of the Inner Bluegrass Karst Region, but are believed to apply as well to most of the rest of the region. A possible exception is that part of the region adjacent to the Kentucky River and the downstream portion of its major tributaries, which has not been investigated and which may exhibit significant difference from the rest of the region, as discussed in the following section.

F9. Applicability of Findings to Other Karst Areas

These discussion have been based on data obtained and observations made in those portions (about 12% of its area) of the Inner Bluegrass Karst Region which has been investigated. The findings reached are believed to apply to the remainder of the region as well, with the possible exception of the portion adjacent to the Kentucky River and the lower reaches of its major tributaries.

This portion of the region (which probably comprises less than one-quarter of its total area) differs from other portions in ways which may be significant to its sursurface flow. The local relief is higher and hillslopes are generally steeper. The bedrock consists of lower members of the Lexington Limestone and units (Tyrone Limestone, Oregon Formation, and Camp Nelson Limestone) which underlie the Lexington Limestone. Although all of these are carbonate rocks, the units beneath the Lexington Limestone are generally thicker bedded and much more dolomitic. Although there are fewer thin shale partings, there are several beds of bentonite in the lower Lexington Limestone and underlying Tyrone Limestone which may range in thickness up to a meter. Inasmuch as the presence of thin beds of shale in the area studied have made the development of stage three conduits (which are able to erode through the shales) a critical element in producing the delineation between groundwater basins and interbasin areas, their absence in these lower units may suggest that interbasin areas are not present. On the other hand, the thick and continuous bentonite (shale) beds may result in more perched groundwater basins. Other factors which may be significant are the apparent chemical supersaturation of some spring waters, as indicated by travertine deposition, and the highly faulted nature of large portions of this area.

The question naturally arises as to the degree to which the findings of this study can be applied to the extensive karst areas in Kentucky in nearly flat-lying rocks of Mississippian age, which extends north into Indiana and south into Tennessee. In short, there appear to be both similarities and differences. In the intensely studied portion of this area near Mammouth Cave, similarities include the existence of groundwater basins (Quinlan and Ewers, 1981) in which the flow pattern is basically dendritic, the existence of a non-meteoric water system beneath what is probably a rather thin aquifer, and the probability that the potentiometric surface is determined in much of the area by equilibrium channel flow in the major conduits. Some of the differences are that the groundwater basins (and hence flows in the major conduits and springs) are significantly larger, the limestone is more massive and generally without shale partins (which may account for the apparent lack of interbasin areas), and that higher level abandoned conduits (such as those which constitute most of the Mammouth Cave system) are abundant in some portion of the area.

Several of the concepts which have been discussed, such as the characterization of different types of subsurface flow, stages in conduit enlargement, and origin and types of sinkholes, are believed to have general applicability in the study of other karst areas. Because of the vast differences between such areas, however, no attempt should be made to apply any of the findings of this study to other karst areas without a careful examination of their potential validity and utility.

REFERENCES

Allingham, J. W., 1972. Geologic map of the Harrodsburg quadrangle, Mercer and Woodford Counties, Kentucky. U. S. Geological Survey, GQ-1020.

Black, D. F. B., 1964. Geology of the Versailles quadrangle, Kentucky. U. S. Geological Survey, GQ-325.

______________, 1967. Geologic map of the Coletown quadrangle, east-central Kentucky. U. S. Geological Survey, GQ-644.

______________, G. R. Keller, and R. W. Johnson, Jr., 1977. Structural geology, Bouguer gravity, and aeromagnetic intensity for a portion of central Kentucky. Kentucky Geological Survey, 4 sheets.

______________, W. C. MacQuown, Jr., and R. J. DeHaas, 1981. The relation of dolomite associated with faults to the stratigraphy and structure of central Kentucky. U. S. Geological Survey, Professional Paper 1151-A, 19p.

Byrd, P. E., 1981. The effects of two water tracing agents on passive cotton dye detectors. University of Kentucky, M. S. Thesis, 51p.

Cressman, E. R., 1964. Geology of the Tyrone quadrangle, Kentucky. U. S. Geological Survey, GQ-303.

______________, 1967. Geologic map of the Georgetown quadrangle, Scott and Fayette Counties, Kentucky. U. S. Geological Survey, GQ-605.

______________, 1972. Geologic map of the Danville quadrangle, Mercer and Boyle Counties, Kentucky. U. S. Geological Survey, GQ-985.

______________, 1973. Lithostratigraphy and depositional environments of the Lexington Limestone (Ordovician) of central Kentucky. U. S. Geological Survey, Professional Paper 768, 61p.

______________, and S. V. Hrabar, 1970. Geologic map of the Wilmore quadrangle, central Kentucky. U. S. Geological Survey, GQ-847.

Eweres, R. O., 1981. The development of limestone cave systems in the dimensions of length and breadth. McMaster University, Ph.D. Thesis.

______________, and J. F. Quinlan, 1981. Cavern porosity development in limestones: a low dip model from Mammoth Cave, Kentucky. Eighth International Congress of Speleology Proceedings, p. 727-731.

Faust, R. J., 1977. Ground-water resources of the Lexington, Kentucky, area. U. S. Geological Survey, Water Resources Investigations 76-113, 24p.

Fisher, I. S., 1968. Interrelation of mineralogy and texture within an Ordovician Lexington Limestone section in central Kentucky. Jour. of Sedimentary Petrology, V. 38, p. 775-784.

Freeze, R. A., and J. A. Cherry, 1979. Groundwater. Prentice-Hall, 604p.

Hall, F. R., and W. N. Palmquist, Jr., 1960a. Availability of ground water in Bath, Fleming, and Montgomery Counties, Kentucky. U. S. Geological Survey, Hydrologic Investigation Atlas HA-18.

________, and ________, 1960b. Availability of ground water in Clark, Estill, Madision, and Powell Counties, Kentucky. U. S. Geological Survey, Hydrologic Investigation Atlas HA-19.

________, and ________, 1960c. Availability of ground water in Carroll, Gallatin, Henry, Owen, and Trimble Counties, Kentucky. U. S. Geological Survey, Hydrologic Investigation Atlas HA-23.

________, and ________, 1960d. Availability of ground water in Anderson, Franklin, Shelby, and Woodford Counties, Kentucky. U. S. Geological Survey, Hydrologic Investigation Atlas HA-24.

Hamilton, D. K., 1948. Some solution features of the limestone near Lexington, Kentucky. Economic Geology, V. 43, p. 39-52.

____________, 1950. Areas and pricniples of ground-water occurrence in the Inner Bluegrass Region, Kentucky. Kentucky Geological Survey, Series 9, Bull. No. 5, 66p.

Hammer, M. J., and K. A. MacKichan, 1981. Hydrology and quality of water resources. Wiley, 486p.

Hendrickson, G. E., and R. A. Krieger, 1964. Geochemistry of natural waters of the Blue Grass Region, Kentucky. U. S. Geological Survey, Water Supply Paper 1700, 135p.

Hine, G. T., 1970. Relation of fracture traces, joints, and ground-water occurrence in the area of the Bryantsville quadrangle, central Kentucky. Kentucky Geological Survey, Series 10, Thesis Series 3, 27p.

Hopkins, H. T., 1966a. Water resources of the Fayette County area, Kentucky, in application of to land-use planning and engineering in Lexington and Fayette County, Kentucky. U. S. Geological Survey, Open-File Report, p. 1-7.

____________, 1966b. Fresh-saline water interface map of Kentucky. Kentucky Geological Survey, Series 10.

Jillson, W. R., 1945. Geology of Roaring Spring. Roberts Printing Co., Frankfort, Kentucky, 44p.

______________, 1961. Erosion cycles in central Kentucky. Roberts Printing Co., Frankfort, Kentucky, 12p.

Johnson, J. T., 1970. Nonparametric analysis of variables influencing limestone ground water occurrence. University of Kentucky, M. S. Thesis, 41p.

______________, and J. Thrailkill, 1973. Variables affecting well success in a Kentucky limestone aquifer. Journal of Hydrology, V. 20, p. 327-333.

Kanizay, S. P., and E. R. Cressman, 1967. Geologic map of the Centerville quadrangle, central Kentucky. U. S. Geological Survey, GQ-653.

Kind, T. C., 1979. The applicability of cyclic and dynamic approaches of landscape development to the Kentucky Bluegrass. Kentucky Academy of Science Transactions, V. 40, p. 85-95.

Leopold, L. B., M. G. Wolman, and J. P. Miller, 1964. Fluvial processes in geomorphology. Freeman, 522p.

MacQuown, W. C., Jr., 1967. Factors controlling porosity and permeability in the Curdsville Member of the Lexington Limestone. University of Kentucky Water Resources Institute, Research Report No. 7, 80p.

______________, and E. Dobrovolney, 1968. Geologic map of the Lexington East quadrangle, Fayette and Bourbon Counties, Kentucky. U. S. Geological Survey, GQ-683.

Matson, G. C., 1909. Water resources of the Bluegrass region, Kentucky. U. S. Geological Survey, Water Supply Paper 233, p. 1-223.

McCann, M. R., 1978. Hydrogeology of northeast Woodford County, Kentucky. University of Kentucky, M. S. Thesis, 103p.

Meinzer, D. E., 1927. Large springs in the United States. U. S. Geological Survey, Water Supply Paper 557, 94p.

Miller, R. D., 1967. Geologic map of the Lexington West quadrangle, Fayette and Scott Counties, Kentucky. U. S. Geological Survey, GQ-600.

Mull, D. S., 1968. The hydrology of the Lexington and Fayette County, Kentucky area. Lexington and Fayette County Planning Commission, 24p.

Palmquist, W. N., Jr., and F. R. Hall, 1960a. Availability of ground water in Bracken, Harrison, Mason, Nicholas, and Robertson Counties, Kentucky. U. S. Geological Survey, Hydrologic Investigation Atlas HA-16.

_________, and _________, 1960b. Availability of ground water in Boyle, Garrard, Lincoln, and Mercer Counties, Kentucky. U. S. Geological Survey Hydrologic Investigation Atlas, HA-20.

________, and ________, 1960c. Availability of ground water in Bourbon, Fayette, Jessamine, and Scott Counties, Kentucky. U. S. Geological Survey Hydrologic Investigation Atlas, HA-25.

________, and ________, 1961. Reconnaissance of ground-water resources in the Blue Grass Region, Kentucky. U. S. Geological Survey, Water Sypply Paper 1533, 39p.

Pomeroy, J. S., 1968. Geologic map of the Frankfort East quadrangle, Franklin and Woodford Counties, Kentucky. U. S. Geological Survey, GQ-707.

____________, 1970. Geologic map of the Midway quadrangle, central Kentucky, U. S. Geological Survey, GQ-856.

Quinlan, J. F., 1977. New fluorescent direct dye suitable for tracing groundwater and detection. Third International Symposium of Underground Water Tracing Paper, V. 2, p. 257-262.

____________, and R. O. Ewers, 1981. Hydrogeology of the Mammoth Cave region, Kentucky. Geological Society of America, Field Trip Guidebook, p. 457-506.

____________, and D. R. Rowe, 1977. Hydrology and water quality in the Central Kentucky Karst: Phase I. University of Kentucky Water Resources Institute, Research Report No. 101, 93p.

Smith, M. O., 1966. Geology and successful farm ponds in the Inner Blue Grass Region of Kentucky. Kentucky Geological Survey, Series 10, Thesis Series 1, 64p.

Society of Dyers and Colourists, 1971. Colour Index, 3rd ed., 6411p.

Spangler, L. E., 1982. Karst hydrogeology of northern Fayette and southern Scott Counties, Kentucky. University of Kentucky, M. S. Thesis, 103p.

____________, and J. Thrailkill, 1981. Hydrogeology of northern Fayette County and southern Scott County, Kentucky, USA. Eighth International Congress of Speleology Proceedings, p. 553-555.

Sweeting, M. M., 1973. Karst Landforms. Columbia University Press, 362p.

Thrailkill, J., 1968. Chemical and hydrologic factors in the excavation of limestone caves. Geological Society of America Bulletin, V. 79, p. 19-46.

____________, 1980. Inner Bluegrass Karst Region (abstract). Proceedings of the Kentucky Water Resources Institute, p. 25.

__________, P. E. Byrd, W. H. Hopper, Jr., M. R. McCann, L. E. Spangler, J. W. Troester, D. R. Gouzie, and K. R. Pogue, 1981. The Inner Bluegrass Karst Region, Kentucky: an overview. Eighth International Congress of Speleology Proceedings, p. 336-338.

__________, __________, S. B. Sullivan, C. J. Taylor, L. E. Spangler, G. K. Nelson, and K. R. Pogue. Studies in dye-tracing techniques and karst hydrogeology. Completion Report, Part 2, for Project B-064-KY, Kentucky Water Resources Research Institute, in preparation.

__________, W. Hopper, Jr., M. McCann, and J. Troester, 1980. Problems associated with urbanization in the Inner Bluegrass Karst Region (abstract). Association of American Geographers, Annual Meeting Program Abstracts, p. 112.

__________, and T. L. Robl, 1981. Carbonate geochemistry of vadose water recharging limestone aquifers. Journal of Hydrology, V. 54, p. 195-208.

__________, and J. W. Troester, 1978. Preliminary, supplemental, and final reports on hydrogeology of Georgetown, Kentucky, in A report to assist the U. S. Water Resources Council in preparing a water assessment of the coal gasification demonstration project, Georgetown, Kentucky. G. Reynolds Watkins, Lexington, Kentucky, p. E1-E14.

__________, __________, L. S. Spangler, and S. J. Cordiviola. Nature of a groundwater basin divide near Georgetown, Inner Bluegrass Karst Region, Kentucky, USA, in Karst hydrogeology, P. LaMoreaux and A. Burger, eds., International Association of Hydrogeologists, accepted for publication.

U. S. Geoloigcal Survey, 1981. Water resources data for Kentucky. Water-Data Report KY-80-1, 804p.

Van Couvering, J. A., 1962. Characteristics of large springs in Kentucky. Kentucky Geological Survey, Series 10 Information Circular 8, 37p.

White, W. B., 1977. Role of solution kinetics in the development of karst aquifers, in Karst hydrogeology, J. S. Tolson and F. L. Doyle, eds., Twelfth Congress of the International Association of Hydrogeologists Memoirs, p. 503-517.

Whitesides, D. V., 1971. Yields and specific capacities of bedrock wells in Kentucky. Kentucky Geological Survey, Series 10, Information Circular 21, 18p.

APPENDIX 1: RESULTS OF DYE TRACES

A total of 142 dye introductions were made in determining flow connections, each of which is shown as a separate entry in the following tabulation. Of these, 121 were original dye introductions and 21 were downstream segments of serial traces (dye detected at successive points along a flow path). Twenty-four of the original dye introductions were not detected and did not result in a trace (although some provided useful negative information). Eighteen of the 118 successful traces were duplicates and in 4 the flow was on the surface for most or all of the flowpath. The average length of the 96 non-surface and non-duplicate traces was about 2.7 km and the longest trace was 15.03 km.

Dye introductions or detections were made in 39 of the 329 2.5 minute quadrangles in the Inner Bluegrass Karst Region. Although many such quadrangles were not thoroughly investigated, their 660 km^2 area, about 12% of the total area of the region (5600 km^2), represents a rough estimate of the extent of the field investigations to date.

Explanation of Tables

The data for each trace is shown in 17 lines, as follows:

1. Dye Introduction Number (DYE INTRO NO): Arranged alphabetically by area and field investigator: A, Northeast Woodford County area (McCann); B, Northern Fayette and Southern Scott counties area (Troester); C, Mercer County area (Hopper); D, Northern Fayette and Southern Scott counties area (Spangler): E, Walnut Hill area (Gouzie). Order is then chronological (by dye introduction time and date). Lower case letter indicates segments of serial trace. Undetected dye introduction indicated by (X), duplicate trace by (D), surface trace by (S).

2. Dye Type/Number/Quantity (D TP/NO/QNT). Dye types are OB, optical brightener; DY, direct yellow; AR, acid red, FL fluorescein. Number is sequential accession number identifying batch. Quantity of dye (as received) is liters for liquid dye (OB) and kilograms for solid dyes (DY,AR,FL).

3. Dye Introduction Site Name (INT SITE NME). Contracted to maximum of 10 characters and spaces.

4. Introduction Site Quadrangle (INT S QUAD). First 4 letters are contracted name of 7.5 minute quadrangle: CENV, Centerville; CLTN, Coletown; DANV, Danville: FRFE, Frankfort East; GEOR, Georgetown; HRDB, Harrodsburg, LEXE, Lexington East; LEXW, Lexington West; MIDW, Midway; TYRN, Tyrone; VERS, Versailles. Two letters which follow indicate 2.5 minute quadrangle (NW, northwest; NC, north-center; CC, center; etc.).

5. Introduction Site Coordinates (INT S COOR): Location within (1:24000) 2.5 minute quadrangle in inches east followed by inches north of southwest corner. This line and the preceding line constitute the LT system of coordinates.

6. Introduction Site Elevation / Discharge (INT S EL/DIS): Elevation in meters and approximate discharge in liters/second. Dash indicates no record, T is liters from water truck, N is no flow.

7. Introduction Time / Date (INT TM/DATE): Time (24-hour clock) and date (day-month-year) of dye introduction. In second and later segments of serial traces, earliest and latest times of introduction are the earliest time of first arrival (or initial introduction time, if later) and the latest time of first arrival of the preceding segment, respectively. These are indicated by enclosing the appropriate dye introduction number and table entries in parentheses.

8. Dye Detection Site Name (DET SITE NME): See 3 above.

9. Detection Site Quadrangle (DET S QUAD): See 4 above.

10. Detection Site Coordinates (DET S COORD): See 5 above.

11. Detection Site Elevation/Mean Discharge (D S ELEV/M DIS): See 6 above. Mean discharge calculated from available approximate discharges between introduction time and latest time of first arrival.

12. First Arrival Earliest Time / Date (F A EAR TM/D): Time and date (see 7 above) of emplacement of first positive detector.

13. First Arrival Latest Time / Date (F A LAT TM/D): Time and date (see 7 above) of removal of first positive detector.

14. Distance / Concentration Determined (DIST/CONC DT): Straight-line distance in km calculated from location of introduction and detection sites. Distance for surface traces from topographic maps. Concentration of dye on detectors is A, low; B, moderate; C, high.

15. Elevation Difference / Gradient (EL DIF/GRAD): Elevation difference in meters calculated from elevation of introduction and detection sites. Gradient (dimensionless) calculated from distance and elevation difference.

16. Minimum/Maximum Travel Time (MIN/MAX T T): Minimum travel time in hours calculated from introduction time (or latest time for serial traces) and first arrival earliest time. Maximum from introduction time (earliest time for serial traves) and first arrival latest time.

17. Maximum/Minimum Velocity (MAX/MIN VEL): Velocity in meters/second calculated from travel times and distance.

1	DYE INTRO NO	A1a	A1b	A1c	A2(D)	A3a	A3b(D)
2	D TP/NO/QNT	OB/1/23.5	OB/1/23.5	OB/1/23.5	DY/2/0.9	DY/2/1.0	DY/2/1.0
3	INT SITE NME	BIG SINK	GAY SINK	SP STA SP	SIMMS SINK	KTCHN SINK	GAY SINK
4	INT S QUAD	VERS CC	MIDW SW	MIDW SW	MIDW SW	VERS NC	MIDW SW
5	INT S COORD	0.55 5.60	2.50 0.10	1.05 5.85	0.75 6.70	0.60 4.05	2.50 0.10
6	INT S EL/DIS	262/84	243/28	234/56	230/-	251/7	243/180
7	INT TM/DATE	1300/310776	(A1a 12 13)	(A1 b12 b13)	1545/080177	1100/190277	(A3 a7 a13)
8	DET SITE NME	GAY SINK	SP STA SP	ROARING SP	ROARING SP	GAY SINK	SP STA SP
9	DET S QUAD	MIDW SW	MIDW SW	FRFE EC	FRFE EC	MIDW SW	MIDW SW
10	DET S COORD	2.50 0.10	1.05 5.85	3.80 3.35	3.80 3.35	2.50 0.10	1.05 5.85
11	D S EL/N DIS	243/28	234/56	219/50	219/42	243/180	234/450
12	P A EAR TNL/D	1245/300876	1200/100976	1115/240976	1300/080177	0900/170277	0915/170277
13	F A LAT TM/D	1100/030976	0920/130976	1445/280976	1500/120177	0830/210277	1115/240277
14	DIST/CONC DT	6.38/C	3.62/B	3.68/B	3.14/C	3.34/B	3.62/B
15	EL DIF/GRAD	19/.0030	9/.002	15/.0041	11/.0035	8/.002	9/.002
16	MIN/MAY T T	718.2/814.0	169.0/379.9	217.4/433.2	0/95.2	0/44.5	0/119.8
17	MAX/MIN VEL	.0025/.0022	.0059/.0026	.0047/.0024	-/.0092	-/.0208	-/.0084

1	A4a	A4b(S)	A5	A6	A7a	A7b(D)	B1
2	DY/2/1.0	DY/2/1.0	DY/2/0.5	AR/4/0.5	DY/2/0.5	DY/2/0.5	DY/3/1.5
3	SINK 62	SPRING 13	WELLS SINK	HOSP SINK	SWOPES CV	GAY SINK	SENG SINK
4	VERS NW	VERS NW	VERS WC	VERS WC	VERS NW	MIDW SW	GEOR CC
5	0.92 5.00	1.25 2.00	4.67 5.80	4.10 2.30	4.85 5.85	2.50 0.10	4.63 4.56
6	267/-	248/80	266/-	269/-	256/-	243/110	265/-
7	1330/150377	(A4 a7 a13)	1030/230477	0800/280477	1430/250577	(A7 a12 a13)	1533/280677
8	SPRING 13	CAMDEN CR	PIN OAK SP	VERSLLS SP	GAY SINK	SP STA SP	ROYAL SP
9	VERS NW	TYRN NE	VERS WC	VERS WC	MIDW SW	MIDW SW	GEOR NC
10	1.25 2.00	5.95 0.45	0.92 7.05	2.60 2.05	2.50 0.10	1.05 5.85	3.03 0.00
11	248/80	245/140	256/10	259/80	243/110	234/130	245/-
12	-/-	1230/150377	1240/190477	0900/280477	1000/270577	1215/210577	(NOT RECOR)
13	1030/190377	1415/170377	1130/290477	1030/290477	1030/280577	1230/040677	(NOT RECOR)
14	1.84/C	1.51/C	2.41/C	0.93/A	1.82/C	3.26/B	2.08/A
15	19/.010	3/.002	10/.0041	10/.011	13/.0072	9/.002	20/.0096
16	0/92.0	0/-	0/144.0	1.0/25.5	43.5/67.0	0/193.5	-/-
17	-/.0056	-/-	-/.0046	.26/.010	.012/.0075	-/.0052	-/-

1	DYE INTRO NO	B2(D)	B3	B4(X)	B5(X)	B6(S)	B7
2	D TP/NO/QNT	DY/3/3.0	DY/3/6.0	DY/3/3.0	FL/-/0.3	DY/3/8.0	DY/5/5.0
3	INT SITE NME	SENG SINK	SHARP DI	NEPARK 1	LAUND WELL	NEPARK 2	GAINESWAY
4	INT S QUAD	GEOR CC	GEOR EC	GEOR EC	GEOR NC	GEOR EC	GEOR EC
5	INT S COORD	4.63 4.56	2.07 5.09	0.20 5.29	3.16 0.20	0.32 5.51	1.00 0.81
6	INT S EL/DIS	255/-	252/3800T	275/3800T	248/-	273/-	258/28
7	INT TM/DATE	1445/220777	1330/290777	1515/240877	1430/060977	1545/301177	1415/150578
8	DET SITE NME	ROYAL SP	NE MAIN	(NOT DETEC)	(NOT DETECT)	NE MAIN	ROYAL SP
9	DET S QUAD	GEOR NC	GEOR NC			GEOR NC	GEOR NC
10	DET S COORD	3.03 0.00	5.84 0.83			5.84 0.83	3.03 0.00
11	D S EL/M DIS	245/220	242/-			242/-	245/990
12	F A EAR TM/D	0745/240777	1900/130877			(NOT RECOR)	1100/150578
13	F A LAT TM/D	1145/240777	1800/140877			(NOT RECOR)	1315/160578
14	DIST/CONC DT	2.08/B	2.44/C			2.25/C	3.98/C
15	EL DIF/GRAD	10/.0048	10/.0041			31/.014	13/.0033
16	MIN/MAX T T	41.0/45.0	365.5/388.5			-/-	0/23.0
17	MAX/MIN VEL	.014/.013	.0019/.013			-/-	-/.048

1	B8	C1	C2(D)	C3	C4	C5	C6a
2	DY/5/8.0	OB/1/3.5	OB/1/3.5	OB/1/3.5	OB/1/7.0	OB/1/1.8	OB/1/5.2
3	KCER DI	ISON SW	ISON SW	WINDOW CV	MOORE WELL	ROYALTY SW	ENSMING SK
4	GEOR SE	HRDB SE	HRDB SE	DANV NW	HRDB SC	HRDB SE	HRDB SE
5	3.80 2.21	0.84 1.55	0.84 1.55	4.25 1.89	4.62 3.43	3.12 6.00	4.13 4.86
6	259/-	273/14	273/.28	261/7.9	273/-	273/5.7	278/8.5
7	1915/010778	1430/020978	1510/230978	1645/230978	1600/101078	1330/151078	0900/261078
8	ROYAL SP	BURGIN SP	BURGIN SP	BAK CV SP	BURGIN SP	SHAWN RUN	BOONE SP
9	GEOR NC	HRDB SE	HRDB SE	DANV NW	HRDB SE	HRDB EC	HRDB SE
10	3.03 0.00	4.05 0.50	4.05 0.50	2.50 2.19	4.05 0.50	3.67 0.25	3.90 3.90
11	245/180	262/35	262/17	259/14	262/76	264/14	274/2.8
12	1530/030778	1530/090978	1430/230978	1715/230978	1415/081078	1300/141078	0945/041178
13	1345/050778	1330/160978	1100/300978	1245/300978	1430/141078	1045/211078	1130/111178
14	8.07/A	2.06/A	2.06/C	1.31/C	3.76/C	1.16/C	0.60/C
15	14/.0017	11/.0053	11/.0053	2/.002	11/.0029	9/.0078	13/.022
16	44.2/90.5	169.0/335.0	0/163.8	0.5/164.0	0/94.5	0/141.3	216.8/386.5
17	.051/.025	.0034/.0017	-/.0035	.73/.0022	-/.011	-/.0023	.0008/.00043

1	DYE INTRO NO	C6b	C7	C8	C9	C10	C11(X)
2	D TP/NO/QNT	OB/1/5.2	OB/1/7.0	OB/1/7.0	OB/1/3.5	OB/1/3.5	OB/1/3.5
3	INT SITE NME	BOONE SP	PONY SW	B-3 SW	QUARRY SW	SCULPIN CV	GRIDER SW
4	INT S QUAD	HRDB SE	HRDB SC	DANV NW	HRDB SC	HRBD CC	HRDB SE
5	INT S COORD	3.90 3.90	3.15 5.32	4.40 3.38	2.29 1.09	1.40 4.70	1.09 4.00
6	INT S EL/DIS	274/2.8	271/68	273/34	268/280	270/150	274/150
7	INT TM/DATE	(C5 a12 a13)	1400/010179	1515/010179	1330/120179	1600/140179	1610/200179
8	DET SITE NME	DISTILL ST	BIG SPRING	BAK CV SP	BIG SPRING	SHAWN COP	(NOT DETEC)
9	DET S QUAD	WILM SW	HRDB SW	DANV NW	HRDB SW	HRBD CC	
10	DET S COORD	0.10 1.90	5.33 2.68	2.50 2.19	5.33 2.68	2.94 4.55	
11	D S EL/M DIS	253/22	258/5100	259/2600	258/2900	252/900	
12	F A EAR TM/D	1145/211078	1430/010179	1610/110179	1610/110179	1100/120179	
13	F A LAT TM/D	1215/111178	1100/060179	1730/200179	1730/200179	1535/210179	
14	DIST/CONC DT	1.81/B	2.83/C	2.03/B	2.05/C	1.53/A	
15	EL DIF/GRAD	21/.012	13/.0046	14/.0069	10/.0049	18/.012	
16	MIN/MAX T T	0/170.5	0.5/117.0	0/117.1	0/196.0	0/167.6	
17	MAX/MIN VEL	-/.0030	1.6/.0067	-/.0048	-/.0029	-/.0025	

1	C12	C13(X)	C14	C15	C16	C17(X)	C18
2	OB/1/1.8	OB/1/5.3	OB/1/3.5	OB/1/3.5	OB/1/1.8	OB/1/5.3	DY/8/1.0
3	WOOD SW	INGRAM SK	WAG 8 SW	GRIDER SW	DUVALL CV	INGRAM SK	SEWER SW
4	DANV NC	HRDB SC	DANV NC	HRDB SE	DANV NE	HRDB SC	HRDB SW
5	3.54 4.14	5.14 6.94	4.89 5.66	1.09 4.00	1.15 1.65	5.14 6.94	5.70 6.75
6	282/2.8	270/-	284/2.8	274/5.7	280/8.5	270/28	270/14
7	1530/210179	-/170279	1230/210279	1230/040379	1400/040379	1615/090379	1530/010479
8	RR SP	(NOT DETEC)	BURGIN SP	SHAWN RUN	FAULC CR	(NOT DETEC)	VOTAH SP
9	DANV NC		HRDB SE	HRBD EC	DANV EC		HRDB WC
10	5.10 0.19		4.05 0.50	3.67 0.25	2.20 7.20		0.46 1.50
11	268/520		262/120	264/110	267/89		252/640
12	1135/210179		1200/020379	1115/020379	1505/020379		1600/010479
13	1455/040279		1045/090379	1000/090379	1520/090379		1130/060479
14	2.61/C		3.47/C	2.82/C	1.39/C		3.50/C
15	14/.0054		22/.0063	10/.0035	13/.0094		18/.0051
16	0/335.4		215.5/382.2	0/117.5	0/12.3		0.5/116.0
17	-/.0022		.0045/.0025	-/.0067	-/.0032		1.94/.0084

1	DYE INTRO NO	C19	C20	C21	C22	C23	C24
2	D TP/NO/QNT	OB/1/7.0	OB/1/3.5	DY/8/1.0	OB/1/3.5	DY/8/1.0	OB/9/2.0
3	INT SITE NME	DEAN SW	CRINOID SW	HUFF CAVE	COVE 1 SW	M-1 SW	INGRAM SK
4	INT S QUAD	DANV NC	HRDB SE	DANV NC	DANV NC	HRDB SW	HRDB SC
5	INT S COORD	4.10 7.20	0.85 4.70	1.75 6.00	1.33 0.50	4.51 5.29	5.14 6.94
6	INT S EL/DIS	280/28	272/1.1	267/-	276/57	261/11	274/14
7	INT TM/DATE	1700/010479	1320/270479	1630/270479	1800/230579	1845/230579	1930/230579
8	DET SITE NME	QUARRY RS	SHAWN RUN	EUREKA SP	COVE COMP	HUMANE SP	HART SP
9	DET S QUAD	HRDB SC	HRDB EC	DANV NW	DANV CC	HRDB SW	HRDB EC
10	DET S COORD	2.52 0.70	3.67 0.25	2.70 6.48	3.50 7.40	2.00 4.47	0.72 0.80
11	D S EL/M DIS	267/62	262/40	255/74	274/82	250/110	261/31
12	F A EAR TM/D	1030/060479	0900/270479	1510/270479	1810/230579	1820/230579	1945/230579
13	F A LAT TM/D	1100/130479	0820/050579	1945/050579	1315/020679	1150/020679	1500/020679
14	DIST/CONC DT	1.17/C	2.57/A	3.09/A	1.39/C	1.61/C	1.30/C
15	EL DIF/GRAD	13/.011	10/.0039	12/.0039	2/.001	11/.0068	13/.010
16	MIN/MAX T T	113.5/282.0	0/187	0/195.2	0.2/235.2	0/233.1	0.2/235.5
17	MAX/MIN VEL	.0029/.0011	-/.0038	-/.0044	2.3/.0016	-/.0019	1.45/.0015

1	Dla	Dlb(S)	Dlc(S)	Dld	D2(D)	D3	D4
2	OB/9/7.0	OB/9/7.0	OB/9/7.0	OB/9/7.0	OB/9/3.5	DY/8/2.0	OB/9/7.0
3	SP LAKE SW	SP LAKE SP	SP LK ST 1	SP LK ST 2	GHEGAN SWT	DEEP SP SW	HUGHES SWT
4	LEXW EC	LEXW NE	LEXW NE	LEXW NE	LEXW NE	LEXE CC	LEXW NC
5	3.24 7.36	3.00 0.34	2.54 0.42	1.32 0.40	1.00 0.62	1.65 4.33	4.85 5.50
6	285/14	280/64	277/-	274/-	274/23	293/2.3	274/4.5
7	1300/280979	(Dl a7 al3)	(Dl a7 bl3)	(Dl a7 cl3)	1215/221079	1055/071179	0950/121179
8	SP LAKE SP	SP LK ST 1	SP LK ST 2	LINDSAY SP	LINDSAY SP	RUSSELL SP	SILVER SPS
9	LEXW NE	LEXW NE	LEXW NE	LEXW CC	LEXW CC	CENV SC	LEXW NC
10	3.00 0.34	2.54 0.42	1.32 0.40	4.38 6.45	4.38 6.45	3.44 0.70	1.25 3.75
11	280/-	277/64	274/220	262/360	262/71	271/280	258/120
12	1240/280979	1210/280979	1145/280979	1015/280979	1235/221079	1605/071179	1130/091179
13	1945/051079	1000/051079	1025/051079	1315/051079	1655/261079	1130/141179	1115/161179
14	0.87/C	0.30/B	0.75/B	2.00/A	1.92/C	7.11/B	2.44/C
15	5/.01	3/.01	31/.0040	12/.0060	12/.0060	22/.0031	16/.0066
16	0/164.8	0/165.0	0/165.4	0/168.2	0.3/100.7	5.2/168.6	0/97.4
17	-/.00063	-/.00050	-/.0013	-/.0033	1.6/.0053	.38/.012	-/.0070

1	DYE INTRO NO	D5	D6	D7	D8	D9	D10
2	D TP/NO/QNT	DY/8/2.0	OB/9/3.5	OB/9/7.0	DY/8/2.0	DY/7,8/4.0	OB/9/3.5
3	INT SITE NME	JOYLAND DI	CARPENT SW	BLACKBURN	SCOTTS SW	CANE RUN	MERE SINK
4	INT S QUAD	LEXE NW	LEXW NE	LEXW NC	LEXE NW	LEXW NE	GEOR SC
5	INT S COORD	5.95 0.50	1.82 1.43	5.55 6.10	5.30 1.90	5.70 4.85	0.60 0.95
6	INT S EL/DIS	283/19	280/7.1	274/7.1	283/5.1	265/140	265/1.1
7	INT TM/DATE	1000/301179	1610/051279	1145/171279	1245/020180	1445/190180	1150/220180
8	DET SITE NME	RUSSELL SP	LINDSAY SP	SILVER SPS	RUSSELL SP	ROYAL SP	SLACKS SP
9	DET S QUAD	CENV SC	LEXW CC	LEXW NC	CENV SC	GEOR NC	GEOR WC
10	DET S COORD	3.44 0.70	4.38 6.45	1.25 3.75	3.44 0.70	3.05 0.00	1.10 7.21
11	D S EL/M DIS	271/390	262/110	258/160	271/320	245/1200	232/110
12	F A EAR TM/D	1130/301179	1435/051279	1300/171279	1330/020180	1030/170180	1505/240180
13	F A LAT TM/D	1300/071279	1040/101279	1650/211279	1020/090180	1215/240180	1210/310180
14	DIST/CONC DT	5.20/B	2.61/C	2.99/C	4.64/B	12.11/A	9.08/C
15	EL DIF/GRAD	12/.0023	18/.0064	16/.0054	12/.0026	20/.0017	33/.0036
16	MIN/MAX T T	0/171.0	0/114.5	1.2/101.1	0.8/165.6	0/117.5	51.3/216.3
17	MAX/MIN VEL	-/.0084	-/.0063	.66/.0082	1.7/.0078	-/.029	.049/.012

1	D11(X)	D12	D13	D14	D15	D16	D17(X)
2	DY/7/4.0	OB/9/3.5	OB/9/3.5	OB/9/7.0	OB/9/3.5	OB/9/3.5	OB/9/3.5
3	SNYDER SP	WICKES SI	SEABOLD SW	HAYES SP	TOWNSEN SW	SNYDER SP	MALLORY SP
4	LEXE NW	LEXW EC	LEXW NC	GEOR EC	LEXE NC	LEXE NW	LEXE NW
5	3.75 6.15	3.57 6.72	5.40 6.40	4.65 3.00	0.23 6.81	3.75 6.15	2.25 7.45
6	282/-	286/14	277/2.3	271/3.1	280/4.5	282/14	274/-
7	1130/140280	1415/160280	1640/190280	1630/250280	1240/260280	1325/260280	1215/040380
8	(NOT DETEC)	SP LAKE SP	SILVER SPS	HOLLAND SP	RUSSELL SP	PAXTON SP	(NOT DETEC)
9		LEXW NE	LEXW NC	GEOR EC	CENV SC	LEXE NW	
10		3.00 0.34	1.25 3.75	5.48 3.54	3.44 0.70	3.26 6.60	
11		280/57	258/150	252/14	271/430	279/9.3	
12		1430/160280	1345/190280	1700/250280	1010/210280	1345/260280	
13		0950/190280	1440/260280	1225/280280	1040/280280	1105/280280	
14		0.81/C	3.00/C	0.60/B	2.15/B	0.41/C	
15		6/.007	19/.0063	19/.032	9/.004	3/.007	
16		0.2/67.6	0/166.0	0.5/67.9	0/46.0	0.3/45.7	
17		.90/.0033	-/.0050	.34/0025	-/.013	.34/.0025	

1	DYE INTRO NO	D18	D19	D20	D21	D22(X)	D23
2	D TP/NO/QNT	OB/9/3.5	OB/9/3.5	DY/7/4.0	OB/9/7.0	OB/9/7.0	DY/7/1.0
3	INT SITE NME	SNOWDEN SW	QUARRY SWT	MALLORY SP	SLACKS CA	FISTER SI	TUCKER CA
4	INT SITE QUAD	LEXE NC	LEXW NC	LEXE NW	GEOR WC	LEXW EC	LEXW WC
5	INT S COORD	1.17 6.60	5.20 4.98	2.25 7.45	2.25 3.78	3.87 5.08	4.00 3.33
6	INT S EL/DIS	280/28	273/.20	274/-	245/-	286/-	274/60
7	INT TM/DATE	1145/110380	1350/110380	1215/130380	1430/130380	0945/200380	2000/200380
8	DET SITE NME	RUSSELL SP	SILVER SPS	(NOT DETEC)	SLACKS SP	(NOT DETEC)	STEELES SP
9	DET S QUAD	CENV SC	LEXW NC		GEOR WC		LEXW WC
10	DET S COORD	3.44 0.70	1.25 3.75		1.10 7.21		3.20 5.70
11	D S EL/M DIS	271/770	258/200		232/180		262/600
12	F A EAR TM/D	1630/060380	1445/110380		1330/130380		1600/200380
13	F A LAT TM/D	1040/130380	1410/180380		1215/200380		1100/250380
14	DIST/CONC DT	1.72/B	2.52/B		2.20/C		1.52/B
15	EL DIF/GRAD	9/.005	15/.0060		13/.0059		12/.0079
16	MIN/MAX T T	0/46.9	0.9/168.2		0/165.8		0/111.0
17	MAX/MIN VEL	-/.010	.76/.0042		-/.0037		-/.0038

1	D24	D25	D26	D27(X)	D28(X)	D29a	D29b
2	DY/7/2.0	OB/9/3.5	OB/9/3.5	OB/9/3.5	OB/9/3.5	OB/9/7.0	OB/9/7.0
3	TODD SWALT	HUGHES SP	GREENUP SW	TACKETT SW	IVY SWALT	ALYEA SWLT	SLOANES SP
4	LEXE NC	LEXW NC	MIDW SE	GEOR WC	CENV SW	GEOR WC	GEOR WC
5	0.92 0.44	5.30 7.15	5.93 0.80	1.43 5.30	5.91 0.17	3.60 1.52	3.45 2.30
6	286/28	280/1.1	259/3.4	248/-	281/-	249/47	247/280
7	1120/200380	1400/010480	1510/030480	1700/030480	1350/100480	1700/170480	(D30 a7 a13)
8	RUSSELL SP	SILVER SPS	SANTEN SP	(NOT DETEC)	(NOT DETEC)	SLOANES SP	SLACKS CA
9	CENV SC	LEXW NC	MIDW SE			GEOR WC	GEOR WC
10	3.44 0.70	1.25 3.75	3.76 3.86			3.45 2.30	2.25 3.78
11	271/850	258/170	241/120			247/280	245/-
12	1155/200380	1315/010480	1725/010480			1515/170480	1545/170480
13	1025/270380	1315/080480	1400/080480			1430/240480	1415/240480
14	5.02/A	3.22/B	2.29/C			0.48/B	1.16/B
15	15/.0030	22/.0068	18/.0079			2/.004	2/.002
16	0.6/167.1	0/167.2	0/118.8			0/165.5	0/165.2
17	2.4/.0083	-/.0054	-/.0053			-/.0081	-/.0020

1	DYE INTRO NO	D30	D31(X)	D32	D33a	D33b(D)	D34
2	D TP/NO/QNT	OB/9/3.5	DY/7/2.0	OB/9/3.5	OB/9/7.0	OB/9/7.0	OB/9/7.0
3	INT SITE NME	GREAT SWLT	MALLORY SP	LITTLE SWT	WASH SWALT	SLOANES SP	SILO SWALT
4	INT S QUAD	MIDW SE	LEXE NW	MIDW SE	GEOR SW	GEOR WC	LEXW NC
5	INT S COORD	4.45 2.60	2.25 7.45	5.41 2.15	4.47 7.48	3.45 2.30	5.40 1.56
6	INT S EL/DIS	249/4.5	274/5.1	259/.56	262/1.1	247/7.1	271/3.4
7	INT TM/DATE	1840/170480	1250/010580	1325/060580	1800/080580	(D31 a7 a13)	1130/130580
8	DET SITE NME	SANTEN SP	(NOT DETEC)	SANTEN SP	SLOANES SP	SLACKS CA	LINDSAY SP
9	DET S QUAD	MIDW SE		MIDW SE	GEOR WC	GEOR WC	LEXW CC
10	DET S COORD	3.76 3.86		3.76 3.86	3.45 2.30	2.25 3.78	4.38 6.45
11	D S EL/M DIS	241/100		241/15	247/7.1	245/-	262/99
12	F A EAR TM/D	1820/170480		1310/060580	1720/080580	1610/140580	1150/130580
13	F A LAT TM/D	1200/220480		1340/130580	1700/140580	1545/230580	1320/200580
14	DIST/CONC DT	0.88/C		1.45/C	1.59/C	1.16/B	1.75/C
15	EL DIF/GRAD	8/.009		18/.012	15/.0094	2/.002	9/.005
16	MIN/MAX T T	0/113.3		0/168.3	0/143.0	0/357.8	0.3/169.8
17	MAX/MIN VEL	-/.0021		-/.0024	-/.0031	-/.00090	1.5/.0029

1	D35	D36	D37	D38	D39(X)	D40(X)	D41(X)
2	DY/7/2.0	DY/7/2.0	OB/9/7.0	OB/9/3.5	OB/9/3.5	DY/13/4.0	DY/7/1.0
3	HUME SWALT	MCGEE SINK	FERRIS SWT	IVY SWALT	TACKETT SW	C RUN SW	FISTER SI
4	LEXE CC	CENV SW	GEOR SW	CENV SW	GEOR WC	LEXE NW	LEXW EC
5	3.40 3.70	2.70 5.10	1.80 5.12	5.91 0.17	1.43 5.30	0.75 0.07	3.87 5.08
6	289/4.5	268/1.1	255/1.1	281/.20	248/-	277/-	286/-
7	1930/170580	1230/290580	1530/030680	1215/090780	1225/090780	1830/160780	1500/220780
8	BAILEY SP	ELKHORN CR	GANO SP	RUSSELL SP	(NOT DETEC)	(NOT DETEC)	(NOT DETEC)
9	LEXE CC	CENV SW	GEOR SW	CENV SC			
10	3.88 3.31	3.43 7.37	0.28 3.88	3.44 0.70			
11	288/14	256/1.1	252/13	271/280			
12	1215/170580	1200/290580	1510/030680	1115/090780			
13	1700/200580	1130/050680	1250/100680	1110/160780			
14	0.38/C	1.45/A	1.20/C	2.18/B			
15	1/.0026	12/.0083	3/.002	10/.0046			
16	0/69.5	0/167.0	0/165.3	0/166.9			
17	-/.0015	-/.0024	-/.0020	-/.0036			

1	DYE TINRO NO	D42(D)	D43(X)	D44(X)	D45a	D45b(D)	D46
2	D TP/NO/QNT	FL/11/0.5	OB/12/3.5	OB/12/3.5	OB/12/7.0	OB/12/7.0	DY/13/1.0
3	INT SITE NME	GHEGAN SWT	LIBERTY SW	CORNETT SW	WELLS SWLT	SLOANES SP	MCGEE SI
4	INT S QUAD	LEXW NE	LEXE SW	MIDW EC	GEOR CC	GEOR WC	CENV SW
5	INT S COORD	1.00 0.62	5.95 6.27	0.28 2.83	1.22 1.29	3.45 2.30	2.70 5.10
6	INT S EL/DIS	274/38	244/1.1	244/2.8	256/2.3	247/-	268/4.5
7	INT TM/DATE	1030/301080	1030/051180	1420/051180	1645/191180	(D45 a7 a13)	1530/201180
8	DET SITE NME	LINDSAY SP	(NOT DETEC)	(NOT DETECT)	SLOANES SP	SLACKS CA	VAUGHNS SP
9	DET S QUAD	LEXW CC			GEOR WC	GEOR WC	CENV SW
10	DET S COORD	4.38 6.45			3.45 2.30	2.25 3.78	3.63 7.35
11	D S EL/M DIS	262/57			247/-	245/-	256/180
12	F A EAR TM/D	0930/301080			1600/191180	1555/261180	1500/201180
13	F A LAT TM/D	1430/041180			1635/261180	1545/031280	1230/261180
14	DIST/CONC DT	1.92/C			2.38/C	1.16/A	1.48/C
15	EL DIF/GRAD	12/.0063			9/.004	2/.002	12/.0081
16	MIN/MAX T T	0/124.0			0/167.8	0.3/335.0	0/141.0
17	MAX/MIN VEL	-/.0043			-/.0039	1.1/.00096	-/.0029

1	D47	D48	D49a	D49b(D)	D50	D51a	D51b(D)
2	OB/9/3.5	DY/13/6.0	OB/12/7.0	OB/12/7.0	FL/11/.25	OB/12/7.0	OB/12/7.0
3	SELLERS SW	C RUN SW	MALLORY SP	MCGEE SI	TACKETT SW	HAMILTN SP	SLOANES SP
4	GEOR SW	LEXE NW	LEXE NW	CENV SW	GEOR WC	GEOR SC	GEOR WC
5	2.21 5.68	0.75 0.07	2.25 7.45	2.70 5.10	1.43 5.30	0.25 4.84	3.45 2.30
6	259/2.3	277/43	274/1.1	268/4.1	248/3.6	256/.57	247/-
7	1745/031280	1615/041280	1000/070181	(D49 a7 a13)	1445/070181	1615/070181	(D51 a7 a13)
8	GANO SP	ROYAL SP	MCGEE SI	VAUGHNS SP	SLACKS SP	SLOANES SP	SLACKS CA
9	GEOR SW	GEOR NC	CENV SW	CENV SW	GEOR WC	GEOR WC	GEOR WC
10	0.28 3.88	3.05 0.00	2.70 5.10	3.63 7.35	1.10 7.21	3.45 2.30	2.25 3.78
11	252/110	246/1100	268/4.1	256/160	232/14	247/-	245/-
12	1730/031280	1500/031280	0945/070181	1050/070181	1400/070181	1230/070181	1315/070181
13	1700/101280	1325/101280	1120/140181	1145/140181	1345/140181	1435/210181	1455/210181
14	1.61/C	15.03/A	3.20/C	1.48/A	1.18/C	3.51/B	1.16/B
15	7/.004	31/.0021	6/.002	14/.0095	16/.014	0/.003	2/.002
16	0/167.3	0/141.2	0/169.0	0/169.8	0/167.0	0/334.3	0/334.7
17	-/.0027	-/.030	-/.0053	-/.0024	-/.0020	-/.0029	-/.00096

1	DYE INTRO NO	D51c(D)	D52	D53(X)	D54a	D54b(D)	D55(X)
2	D TP/NO/QNT	OB/12/7.0	OB/12/1.75	OB/12/1.75	DY/13/1.0	DY/13/1.0	DY/13/2.0
3	INT SITE NME	SLACKS CA	LEER SW 1	INGELS CA	CASHMAN SW	MCGEE SI	FRYMAN SW
4	INT S QUAD	GEOR WC	MIDW EC	GEOR SE	CENV SW	CENV SW	LEXE WC
5	INT S COORD	2.25 3.78	0.12 4.63	1.40 0.80	3.70 2.22	2.70 5.10	3.55 6.80
6	INT S EL/DIS	245/-	247/1.6	277/-	286/.10	268/13	291/.57
7	INT TM/DATE	(D51 a7 b13)	1445/140181	1700/170181	1345/210181	(D54 27 213)	1215/060281
8	DET SITE NME	SLACKS SP	CORNETT SP	(NOT DETEC)	MCGEE SI	VAUGHNS SP	(NOT DETEC)
9	DET S QUAD	GEOR WC	MIDW EC		CENV SW	CENV SW	
10	DET S COORD	1.10 7.21	0.28 2.83		2.70 5.10	3.63 7.35	
11	D S EL/M DIS	232/14	238/4.5		268/13	256/180	
12	F A EAR TM/D	1400/070181	1450/140181		1220/210181	1300/210181	
13	F A LAT TM/D	1520/210181	1640/280181		1215/280181	1320/280181	
14	DIST/CONC DT	2.21/B	1.10/C		1.86/C	1.48/A	
15	EL DIF/GRAD	13/.0059	9/.008		18/.0097	12/.0081	
16	MIN/MAX T T	0/335.1	0.1/337.9		0/166.5	0/167.6	
17	MAX/MIN VEL	-/.0018	3.1/.00091		-/.0031	-/.0025	

1	D56a	D56b(D)	D56c(D)	D57	D58	D59(X)	D60a
2	DY/13/2.0	DY/13/2.0	DY/13/2.0	OB/12/3.5	OB/12/2.0	OB/12/1.5	DY/13/1.0
3	MEREWTH SW	SLOANES SP	SLACKS CA	ANSLEY SWT	CLEVELD SW	LEER SW 2	PENN SW
4	GEOR SC	GEOR WC	GEOR WC	VERS NE	GEOR SW	MIDW CC	CENV SW
5	0.80 0.10	3.45 2.30	2.25 3.78	5.60 7.00	2.70 3.94	5.55 5.22	2.80 2.65
6	262/7.1	247/180	245/-	259/1.2	265/2.3	250/1.1	277/.057
7	1440/060281	(D56 a7 a13)	(D56 a7 b13)	1520/060281	1630/060281	1750/060281	1415/090281
8	SLOANES SP	SLACKS CA	SLACKS SP	SO ELKH	GANO SP	(NOT DETEC)	MCGEE SI
9	GEOR WC	GEOR WC	GEOR WC	VERS NE	GEOR SW		CENV SW
10	3.45 2.30	2.25 3.78	1.10 7.21	4.82 5.02	0.28 3.88		2.70 5.10
11	247/280	245/-	232/320	244/3000	252/180		268/1.0
12	1250/040281	1315/040281	1350/040281	1530/060281	1455/040281		1015/040281
13	1535/140281	1600/140281	1615/140281	1455/140281	1520/140281		1220/140281
14	6.30/B	1.16/B	2.21/B	1.30/C	1.48/B		1.49/B
15	15/.0024	2/.002	13/.0059	15/.012	13/.0088		0/.006
16	0/192.9	0/193.3	0/193.6	0.2/191.6	0/191.3		0/118.1
17	-/.0091	-/.0017	-/.0032	1.8/.0019	-/.0021		-/.0035

1	DYE INTRO NO	D60b(D)	D61	D62	D63a	D63b(D)	D63C(D)
2	D TP/NO/QNT	DY/13/1.0	FL/11/.08	FL/11/.08	OB/12/3.5	OB/12/3.5	OB/12/3.5
3	INT SITE NME	MCGEE SI	ROBIN SW	ADAMS SWLT	TACK SW 2	SLOANES SP	SLACKS CA
4	INT S QUAD	CENV SW	GEOR WC	GEOR WC	GEOR SC	GEOR WC	GEOR WC
5	INT S COORD	2.70 5.10	0.30 6.90	2.90 1.56	0.50 6.41	3.45 2.30	2.25 3.78
6	INT S EL/DIS	268/1.0	237/9.3	256/19	259/9.3	247/480	245/-
7	INT TM/DATE	D60 a7 a13)	1610/090281	1315/200281	1700/200281	(D63 a7 a13)	(D60 a7 b13)
8	DET SITE NME	VAUGHNS SP	SLACKS SP	SLOANES SP	SLOANES SP	SLACKS CA	SLACKS SP
9	DET S QUAD	CENV SW	GEOR WC	GEOR WC	GEOR WC	GEOR WC	GEOR WC
10	DET S COORD	3.63 7.35	1.10 7.21	3.45 2.30	3.45 2.30	2.25 3.78	1.10 7.21
11	D S EL/M DIS	256/180	232/110	247/480	247/480	245/-	232/5.70
12	F A EAR TM/D	1045/040281	1625/090281	1230/200281	1230/200281	1600/140281	1615/140281
13	F A LAT TM/D	1240/140281	1615/140281	1230/250281	1230/250281	1330/250281	1330/250281
14	DIST/CONC DT	1.48/A	0.52/B	0.56/A	2.82/B	2.21/A	2.21/A
15	EL DIF/GRAD	12/.0081	5/.01	9/.02	12/.0043	13/.0059	13/.0059
16	MIN/MAX T T	0/118.4	0.3/120.1	0/119.3	0/115.0	0/116.5	0/116.5
17	MAX/MIN VEL	-/.0035	.48/.0012	-/.0013	-/.0068	-/.0053	-/.0053

1	D64	D65	D66	D67	D68	D69(X)	D70
2	DY/13/1.0	OB/12/7.0	FL/11/.08	OB/12/1.5	OB/12/2.0	OB/9/3.0	DY/13/1.0
3	CRAIG SINK	INGELS CA	BELL SW	KING PIT	WOOD SP	LEER SW 2	TUTTLE SW
4	MIDW EC	GEOR SE	CENV WC	LEXW WC	CENV WC	MIDW CC	MIDW EC
5	4.13 5.04	1.40 0.80	1.17 1.48	4.60 3.90	1.19 0.28	5.55 5.22	5.12 2.50
6	259/.57	277/1.4	259/9.3	263/110	264/.57	250/.57	259/2.3
7	1645/250281	1750/250281	1845/250281	1800/030381	1250/100381	1630/100381	1000/120381
8	NANCE SP	SILVER SPS	TEVIS SP	STEELES SP	TEVIS SP	(NOT DETEC)	NANCE SP
9	MIDW NE	LEXW NC	CENV WC	LEXW WC	CENV WC		MIDW NE
10	3.25 1.45	1.25 3.75	1.85 1.70	3.21 5.68	1.85 1.70		3.25 1.45
11	230/-	258/180	256/67	262/410	256/30		230/-
12	1545/250281	1110/250281	1830/250281	1300/280281	1140/100381		1500/100381
13	1615/030381	1735/030381	1100/030381	1300/070381	1140/170381		1240/170381
14	2.49/B	4.69/C	0.44/B	1.38/B	0.95/C		4.14/C
15	29/.012	19/.0041	3/.007	1/.0007	8/.008		29/.0070
16	0/143.5	0/143.8	0/136.3	0/91.0	0/166.8		0/122.7
17	-/.0048	-/.0091	-/.00089	-/.0042	-/.0016		-/.0094

1	DYE INTRO NO	D71(D)	D72	D73(X)	D74(X)	D75(X)	D76
2	D TP/NO/QNT	FL/11/.12	FL/11/.12	DY/13/1.0	DY/13/1.0	FL/11/.25	OB/12/3.5
3	INT SITE NME	LEER SW 1	JENNING SW	TRAILER SW	CORNETT SW	LEER SW 2	GREENES CA
4	INT S QUAD	MIDW EC	GEOR CC	MIDW EC	MIDW EC	MIDW CC	MIDW NE
5	INT S COORD	0.12 4.63	0.82 5.19	4.55 1.38	2.75 2.65	5.55 5.22	5.25 7.24
6	INT S EL/DIS	247/9.3	256/2.3	252/2.3	244/14	250/.57	253/1.7
7	INT TM/DATE	1450/170381	1510/200381	1630/240381	1630/270481	1500/040581	1630/080581
8	DET SITE NME	CORNETT SP	JENNING SP	(NOT DETEC)	(NOT DETEC)	(NOT DETEC)	BLUE SP
9	DET S QUAD	MIDW EC	GEOR CC				MIDW NE
10	DET S COORD	0.28 2.83	0.08 3.47				4.51 4.26
11	D S EL/M DIS	238/12	243/18				232/47
12	F A EAR TM/D	1340/170381	1415/200381				1245/080581
13	F A LAT TM/D	1530/240381	1405/240381				1210/140581
14	DIST/CONC DT	1.10/C	1.14/C				1.87/C
15	EL DIF/GRAD	9/.008	13/.011				21/.011
16	MIN/MAX T T	0/168.7	0/95.1				0/139.7
17	MAX/MIN VEL	-/.0018	-/.0033				-/.0037

1	D77	D78	D79	D80	E1	E2
2	OB/12/1.5	OB/12/7.0	FL/11/.12	DY/13/4.0	OB/12/3.5	OB/12/3.5
3	CORNETT SW	HALL SINK	WILEY SP	BRUNER SW	BRUMAG SW	DOWNING SK
4	MIDW EC	MIDW EC	GEOR WC	LEXW NE	CLTN EC	CLTN EC
5	2.75 2.65	5.25 1.25	2.11 1.19	4.10 7.05	1.22 7.28	2.99 6.83
6	244/9.3	259/2.8	265/1.7	265/14	315/N	300/.28
7	0900/160581	1400/210581	1330/230581	1215/250581	1440/291080	1500/240381
8	ELKHORN SP	NANCE SP	SLOANES SP	ROYAL SP	BOGGS CAVE	I-75 POND
9	MIDW EC	MIDW NE	GEOR WC	GEOR NC	CLTN EC	CLTN EC
10	2.02 2.22	3.25 1.45	3.45 2.30	3.05 0.00	2.71 5.39	4.03 6.53
11	238/35	230/-	247/5.30	246/1200	288/.76	288/4.2
12	1400/140581	1600/210581	1345/230581	1300/250581	1515/121180	1550/220381
13	1230/210581	1300/300581	1300/280581	1400/300581	1430/191180	1345/290381
14	0.52/C	4.90/C	1.06/A	10.49/A	1.47/C	0.66/C
15	6/.012	29/.0059	18/.017	19/.0018	27/.018	12/.018
16	0/123.5	2.0/215.0	0.3/119.5	0.8/121.8	337.3/504.5	0/118.8
17	-/.070	.68/.0063	0.98/.0025	3.6/.024	.0012/.00081	-/.015

APPENDIX 2 - SPRING LOCATIONS AND DYE INTRODUCTIONS

The following table gives locations (in LT coordinates - see section A2) of springs in or discussed with a groundwater basin. Also listed are the numbers of all dye introductions performed in or near each groundwater basin.

Number and Name of Basin (Report Section)	Number and Name of Spring (Location)	Dye Introduction Numbers
2. Baker Cave Spring basin (C1h)	2. Baker Cave Spring (DANV NW 2.50 2.19)	C3, C8
3. Big Spring basin (C1a)	3. Big Spring (HRDB SW 5.33 2.68)	C7, C9, C19
4. Blue Spring basin (D1k)	4. Blue Spring (MIDW NE 4.51 4.26)	D76
5. Boggs Spring basin (E1a)	5. Boggs Spring (CLTN EC 2.71 5.39)	E1
8. Burgin Spring basin (C1b)	8. Burgin Spring (HRDB SE 4.05 0.50)	C1, C2(D), C4, C14
10. Cornett Spring basin (D1j)	10. Cornett Spring (MIDW EC 0.28 2.83)	D52, D59(X), D69(X), D71(D), D75(X)
11. Cove Spring basin (C1g)	11. Cove Spring (DANV CC 3.50 7.40)	C22
12. Distillery Spring basin (C1c)	6. Boone Spring (HRDB SE 3.90 3.90) 12. Distillery Spring (HRDB SE 4.80 2.65)	C6a, C6b
13. Elkhorn Spring basin (D1j)	13. Elkhorn Spring (MIDW EC 2.02 2.22)	D44(X), D74(X), D77
14. Eureka Spring basin (C1i)	14. Eureka Spring (DANV NW 2.70 6.48)	C21
15. Gano Spring basin (D1g)	15. Gano Spring (GEOR SW 0.28 3.88)	D37, D47, D58
17. Hartman Spring basin (C1e)	17. Hartman Spring (HRDB EC 0.72 0.80)	C13(X), C17(X), C24
18. Holland Spring basin (D1i)	18. Holland Spring (GEOR EC 5.48 3.54)	D14
19. Humane Spring basin (C1i)	19. Humane Spring (HRDB SW 2.00 4.47)	C23

20. I-75 Pond Spring basin (E1b)	20. I-75 Pond Spring (CLTN EC 4.03 6.53)	E2
21. Jenning Spring basin (D1k)	21. Jenning Spring (GEOR CC 0.08 3.47)	D72
22. Lindsay Spring basin (D1d)	22. Lindsay Spring (LEXW CC 4.38 6.45)	D1b(S), D1c(S), D1d, D2(D), D6, D34, D42(D)
24. Nance Spring basin (D1h)	24. Nance Spring (MIDW NE 3.25 1.45)	D64, D70, D73(X), D78
26. Pin Oak Spring basin (B1b)	26. Pin Oak Spring (VERS WC 0.92 7.05)	A5
27. Railroad Spring basin (C1i)	27. Railroad Spring (DANV NC 5.10 0.19)	C12
28. Roaring Spring basin (B1a)	9. Cogar Spring (MIDW SC 2.50 2.68) 16. Gay Sink Spring (MIDW SW 2.50 0.10) 28. Roaring Spring (FRFE EC 3.80 3.35) 40. Spring Station Spring (MIDW SW 1.05 5.85) 42. Swopes Spring (VERS NW 4.60 5.70) 49. Wests Spring (MIDW SC 3.10 1.25)	A1a, A1b, A1c, A2(D), A3a, A3b(D), A7a, A7b(D)
29. Royal Spring basin (D1a)	29. Royal Spring (GEOR NC 3.03 0.00)	B1, B2(D), B5(X), B7, B8, D9, D40(X), D48, D55(X), D80
30. Russell Cave Spring basin (D1b)	1. Bailey Spring (LEXE CC 3.88 3.31) 30. Russell Cave Spring (CENV SC 3.44 0.70)	D3, D5, D8, D15, D18, D24, D28(X), D35, D38, D43(X)
31. Santen Spring basin (D1j)	31. Santen Spring (MIDW SE 3.76 3.86)	D26, D30, D32
32. Shawnee Copperhead Spring basin (C1f)	32. Shawnee Copperhead Spring (HRDB CC 2.94 4.55) 33. Shawnee Hefer Spring (HRDB CC 3.25 4.10)	C10
34. Shawnee Run Spring basin (C1d)	34. Shawnee Run Spring (HRDB EC 3.67 0.25)	C5, C11(X), C15, C20

35. Silver Springs basin (D1e)	35. Silver Springs (LEXW NC 1.25 3.75)	D4, D7, D13, D19, D25, D53(X), D65
36. Slacks Spring basin (D1f)	36. Slacks Spring (GEOR WC 1.10 7.21) 37. Slacks Cave (GEOR WC 2.25 3.78) 38. Sloanes Spring (GEOR WC 3.45 2.30)	D10, D11(X), D21, D27(X), D29a, D29b, D33a, D33b(D), D39(X), D45a, D45b(D), D50, D51a, D51b(D), D51c(D), D56a, D56b(D), D56c(D), D61, D62, D63a, D63b(D), D63c(D), D79
39. Spring Lake Spring basin (D1d)	39. Spring Lake Spring (LEXW NE 3.00 0.34)	D1a, D12, D22(X), D41(X)
41. Steeles Spring basin (D1k)	41. Steeles Spring (LEXW WC 3.20 5.70)	D23, D67
43. Tevis Spring basin (D1i)	43. Tevis Spring (CENV WC 1.85 1.70)	D66, D68
44. Spring 13 basin (B1b)	44. Spring 13 (VERS NW 1.25 2.00) 45. Spring 13B (VERS NW 1.40 2.16)	A4a, A4b(S)
46. Vaughans Spring basin (D1c)	23. McGee Sink (CENV SW 2.70 5.10) 25. Paxton Spring (LEXE NW 3.26 6.60) 46. Vaughans Spring (CENV SW 3.63 7.35)	D16, D17(X), D20(X), D31(X), D36, D46, D49a, D49b(D), D54a, D54b(D), D60a, D60b(D)
47. Versailles Spring basin (B1b)	47. Versailles Spring (VERS WC 2.60 2.05)	A6
48. Votah Spring basin (C1i)	48. Votah Spring (HRDB WC 0.46 1.50)	C18
B3. Sharp Swallet basin (D1i)	-	B3, B4(X), B6(S)
C16. Duvall Cave basin (C1i)	-	C16
D57. Ansley Swallet basin (D1j)	-	D57

APPENDIX 3 - NEGATIVE DYE DETECTION

The following lists, for each dye introduction (Appendix 1), sites which were monitored throughout the period of the trace at which dye was not detected. This record is not complete, and failure to detect a dye introduction may be due in some cases to factors other than lack of a flow connection, such as an insufficient amount of dye used or dilution by high flows at the detection point. These data, however, may be useful in cases where evidence is needed regarding the lack of a flow connection.

Site names have been abbreviated to a maximum of ten letters and spaces. Locations in parentheses are LT coordinates (see section A2). Where no location is listed it will be found in previous entries in the table or in Appendix 1, usually as a detection point.

A1a: BIG SINK SP (VERS CC 0.40 5.35), CAMDEN CR, COGAR SP (MIDW SC 2.50 2.68), GRAS SP RD (TYRN NC 3.65 6.00), GRISWOLD W (VERS NC 1.20 7.20), PIN OAK SP, ROARING SP, SP STA SP, VERSLLS SP.

A1b: Same as A1a except BIG SNK SP and SP STA SP.

A1c: Same as A1a except BIG SNK SP, SP STA SP, and ROARING SP.

A2(D): Same as A1a except BIG SNK SP and ROARING SP.

A3a: CAMDEN CR, COGAR SP, GRISWOLD W, LEES BRNCH (MIDW SC 2.65 0.65), PIN OAK SP, ROARING SP, SHIPPS WL (VERS NW 3.90 7.10), S ELKHORN (FRFE EC 3.70 3.55), SP STA SP, SWOPES SPR (VERS NW 4.60 5.75), VERSLLS SP, WESTS SP (MIDW SC 3.10 1.25).

A3b(D): Same as A3a except SP STA SP.

A4a: BEALS RUN (FRFE SE 5.15 3.35), COGAR SP, GAY SINK, GRISWOLD W, LEES BRNCH, PIN OAK SP, ROARING SP, S ELKHORN, SP MM59 (TYRN NE 3.70 7.43), SP STA SP, ST MM57 (TYRN NE 5.10 2.00), ST MM58 (TYRN NE 0.40 1.75), VERSLLS SP, WESTS SP.

A4b(S): Same as A4a.

A5: BIG SNK SP, CAMDEN CR, COGAR SP, GAY SINK, PIN OAK SP, ROARING SP, SP STA SP, SPRING 13 (VERS NW 1.25 2.00), SPRING 13B (VERS NW 1.40 2.16), STRM 13F (VERS NW 1.52 2.25), VERSLLS SP.

A7a: Same as A5 except GAY SINK.

A7b(D): Same as A5 except GAY SINK and SP STA SP.

B3: NE QUARRY (GEOR EC 2.47 6.45), ROYAL SP.

B4(X): N BRDAD (GEOR NC 2.95 1.94), NE MAIN, NE QUARRY, ROYAL SP.

B5(X): ROYAL SP.

B6(S): NE QUARRY, ROYAL SP

C1: BAK CV SP, BIG SPRING, BOONE SP, CEDAR BR (WILM WC 3.60 0.60), COVE COMP (DANV CC 3.50 7.40), DISTILL ST, SHAKER CR (HRDB EC 4.70 4.75), SHAWN RUN.

C2(D): Same as C1 except COVE COMP and SHAKER CR.

C3: BIG SPRING, BOONE SP, BURGIN SP, CANE RUN BR (DANV NE 5.20 7.50), CEDAR BR, DISTILL SP, SHAWN RUN.

C4: Same as C3 except BURGIN SP and CANE RUN BR.

C5: BIG SPRING, BOONE SP, BURGIN SP, CANE RUN BR, CEDAR BR, DISTILL ST.

C6a: BURGIN SP, CANE RUN BR, DISTILL ST, SHAWN RUN

C6b: Same as C6a except DISTILL ST.

C7: BAK CV SP, BURGIN SP, CANE RUN BR, DISTILL ST, SHAWN RUN.

C8: BIG SPRING, BURGIN SP, CANE RUN BR, DISTILL ST, SHAWN RUN.

C9: BAK CV SP, BIG SPRING.

C10: BAK CV SP, BIG SPRING, BUSTER (N) (DANV NE 1.45 5.00), BUSTER (S) (DANV EC 2.30 5.55), FAULC CR (DANV EC 2.20 7.20), RLRD CR (DANV EC 0.05 7.45), SHAWN HEFR (HRDB CC 2.94 4.55).

C11(X): BAK CV SP, BIG SPRING, BURGIN SP, BUSTER (N), BUSTER (S), COVE COMP, FAULC CR, QUARRY RES (HRDB SC 2.52 0.70), RLRD CR, SHAWN HEFR, SHAWN RUN.

C12: Same as C11(X) except BUSTER (S) and RLRD CR.

C13(X): BAK CV SP, BIG SPRING, BURGIN SP, BUSTER (N), COVE COMP, FAULC CR, QUARRY RES, RLRD CR, SHAWN COP (HRDB CC 2.94 4.55), SHAWN HEFR, SHAWN RUN.

C14: BAK CV SP, BIG SPRING, BUSTER (N), COVE COMP, DISTILL ST, FAULC CR, QUARRY RES, RLRD CR, RLRD ST (DANV CC 5.35 7.15), SHAWN COP, SHAWNEE BR (HRDB EC 4.72 4.64), SHAWN HEFR, SHAWN RUN.

C15: Same as C14 plus BURGIN SP except SHAWNEE BR and SHAWN RUN.

C16: Same as C14 plus BURGIN SP except FAULC CR.

C17(X): BIG SPRING, BURGIN SP, DISTILL ST, FAULC CR, QUARRY RES, SHAWN RUN, WLDWD COMP (HRDB CC 4.20 1.60)

C18: BIG SPRING, BURGIN SP, BUSTER (N), CANE RN BL (HRDB SE 3.29 1.55), COVE COMP, DIST ST, EUREKA SP, FAULC CR, HUFF CV, HUMANE SP, RLRD CR, RLRD ST, SALT CR (DANV NW 2.00 6.64)

C19: Same as C18 plus VOTAH SP except BIG SPRING, HUMANE SP, and SALT CR.

C20: BIG SPRING, BURGIN SP, CANE RN BL, EUREKA SP, HART SP, INGRAM SK, QUARRY RES, SHAWN COP, SHAWN HEFR

C21: Same as C20 plus SHAWNEE BR and SHAWN RUN except EUREKA SP.

C22: BIG SPRING, CANE RUN BL, EUREKA SP, HART SP, QUARRY RES, SHAWN RUN, VOTAH SP.

C23: Same as C22 plus COVE COMP.

C24: Same as C22 except HART SP.

D3: BRYAN STAT (LEXE EC 0.20 6.40), HUME SP (LEXE CC 2.75 4.17), WOOD SP (LEXE EC 0.24 6.35)

D4: LINDSAY SP

D5: ROYAL SP

D6: SILVER SPS

D7: LINDSAY SP

D8: ROYAL SP

D9: LINDSAY SP, RUSSELL SP, SILVER SPS

D12: LINDSAY SP

D13: LINDSAY SP

D14: DRAKE ST (GEOR NE 0.03 0.17)

D16: TIPTON SP (LEXE NW 2.95 5.17)

D19: LINDSAY SP

D24: ROYAL SP

D25: LINDSAY SP

D34: SILVER SPS

D35: RUSSELL SP

D36: ROYAL SP, RUSSELL SP

D37: SANTEN SP

D38: MCGEE SINK

D46:	ROYAL SP
D48:	RUSSELL SP, VAUGHNS SP
D51a:	ROYAL SP, GANO SP
D51b:	Same as D51a
D54a:	RUSSELL SP
D54b:	Same as D54a
D57:	SANTEN SP
D59(X):	CORNETT SP
D64:	SLACKS SP
D65:	SLOANES SP, ROYAL SP
D69(X):	CORNETT SP
D70:	CORNETT SP
D71(D):	MOBLEY SP (MIDW CC 5.70 1.75)
D73(X):	NANCE SP
D75(X):	CORNETT SP
D77:	CORNETT SP
E1:	I-75 POND
E2:	BOGGS CAVE

APPENDIX 4 - SPRING DISCHARGES

Springs and discharge observations in the Inner Bluegrass Karst Region. Spring numbers same as Table 2 and Fig. 2-4. Under observer, "Van Couv." is Van Couvering (1962; p. 24 and 37) "H. and K." is Hendrickson and Krieger (1964; p. 85). Total Observations in parentheses indicates data not used to assign spring magnitude. See Appendix 2 for spring locations.

				Spring Magnitude								
				5-	5+	4-	4+	3-	3+	2-	2+	1-
				Number of Discharge Observations in Each Interval (l/s). Median is underlined.								
Spring (Number)	Period (mo-yr)	Observer	Total Obs.	l.t. 1	1- 3	3- 10	10- 30	30- 100	100- 300	300- 1000	1000 3000	g.t. 3000
Baker Cave Spring (2)	0878-0679	Hopper	28	1	2	9	7	6	-	1	1	1
Big Spring (3)	0678-0779	Hopper	42	-	-	-	2	12	13	11	1	13
Boggs Spring (5)	0980-1280	Gouzie	13	2	3	5	3	-	-	-	-	-
Boone Spring (6)	0678-0779	Hopper	30	3	4	8	6	5	3	1	-	-
Burgin Spring (8)	0678-0779	Hopper	38	-	-	-	5	18	11	4	-	-
Cogar Spring (9)	0776-0677	McCann	32	-	19	7	4	2	-	-	-	-
Cornett Spring (10)	0680-0581	Spangler	28	-	-	14	7	5	2	-	-	-
Cove Spring (11)	0878-0779	Hopper	25	1	2	2	9	8	2	-	1	-
Eureka Spring (14)	0379-0779	Hopper	12	-	-	-	1	7	3	-	1	-
Gano Spring (15)	0480-0581	Spangler	36	-	-	1	15	8	12	-	-	-
Gay Sink Spring (16)	0576-0677	McCann	53	-	-	-	5	25	17	2	4	-
Hartman Spring (17)	0479-0679	Hopper	7	-	-	-	3	4	-	-	-	-
Humane Spring (19)	0978-0779	Hopper	24	-	-	-	2	13	6	2	1	-
Lindsay Sprint (22)	0679-0581	Spangler	60	-	-	-	1	21	29	9	-	-
Pin Oak Spring (26)	0776-0577	McCann	28	-	1	19	8	-	-	-	-	-

Spring (Number)	Period (mo-yr)	Observer	Total Obs.	l.t. 1	1- 3	3- 10	10- 30	30- 100	100- 300	300- 1000	1000 3000	g.t. 3000
Roaring Spring (28)	0676-0677	McCann	43	-	-	-	-	8	28	7	-	-
Royal Spring (29)	0277-0778	Troester	131	-	-	-	-	14	39	53	23	2
"	1179-0581	Spangler	70	-	-	-	-	6	17	22	25	-
Russell Cave Spring (30)	1053-0960	Van Couv.	(12)	-	-	2	1	5	2	2		
"	0679-0381	Spangler	76	-	-	-	-	18	31	25	2	-
Santen Spring (31)	0380-0581	Spangler	30	-	1	10	7	3	9	-	-	-
Shawnee Copperhead Spring (32)	0878-0679	Hopper	28	1	2	9	7	6	-	1	1	1
Shawnee Hefer Spring (33)	0878-0779	Hopper	19	-	-	-	5	8	4	1	1	-
Shawnee Run Spring (34)	0678-0779	Hopper	38	-	-	-	9	15	12	1	1	-
Silver Springs (35)	0457-0360	H. and K.	(10)	-	-	2	5	1	2	-	-	-
"	0879-0581	Spangler	56	-	-	-	6	22	27	1	-	-
Slacks Spring (36)	1279-0581	Spangler	48	-	-	-	15	9	12	12	-	-
Sloanes Spring (38)	0480-0581	Spangler	40	19	-	2	3	3	6	7	-	-
Spring Lake Spring (39)	0679-0381	Spangler	32	-	-	1	2	24	5	-	-	-
Spring Station Spring (40)	0954-0460	Van Couv.	10	-	-	-	4	2	3	1	-	-
"	0576-0677	McCann	42	-	-	-	-	27	13	2	-	-
Tevis Spring (43)	0879-0581	Spangler	12	6	5	1	-	-	-	-	-	-
Spring 13 (44)	0377-0577	McCann	7	-	1	3	3	-	-	-	-	-
Spring 13B (45)	0377-0577	McCann	7	1	1	5	-	-	-	-	-	-
Vaughans Spring (46)	0779-0681	Spangler	24	-	-	-	-	2	22	-	-	-
Versailles Spring (47)	0776-0577	McCann	31	-	-	3	18	9	1	-	-	-
Votah Spring (48)	0379-0679	Hopper	8	-	-	-	1	3	2	1	1	-
Wests Spring (49)	0277-0577	McCann	7	-	-	-	-	7	-	-	-	-

APPENDIX 5 - GEORGETOWN QUADRANGLE WELL DATA

Well date for Georgetown Quadrangle. Depth, Elevation (of well head), and Potentiometric Surface elevations (POT) in meters. All potentiometric surface elevations from Mull (1968) and all notes from Hamilton (1950) unless otherwise indicated by M, Mull; H, Hamilton; TT, Thrailkill and Troester (1978); PH, Palimquist and Hall (1960c); and JT, this report. Hamilton's well numbers in notes prefixed by letter indicating five-minute quadrangle by longitude and latitude of southeast corner, as follows: A, 8435-3810; B, 8430-3810; C, 8435-3805; and D, 8430-3805. Wells from different sources with same location assumed the same well if depths reports consistent. Hamilton locations from old small scale maps hence locations on Fig. 9 and 10 approximate. Elevations read from topographic map (1:24,000,3.05 m contour interval) and are uncertain by about one meter even if location is exact. Hamilton notes generally verbatim except for change of units and deletion of driller's name and date drilled.

Well	Depth	Elev.	Pot.	Notes
1	29			A30. Water level 20 m. Water contains some sulfur.
2	38			A14. Water contains iron.
3	14	238	233	
4	4			A15. Dry.
5	63	270	256	
6	27			B30. Water contains some sulfur.
7	28			A33. Water contains sulfur and salt.
8	9	261	251?	
9	24			A13. Water contains lime.
10	25	250	238	A12. Water contains lime. Depth (M). POT (M).
11	30			Yield 3 l/s (PH). Depth (PH).
12	20			A32. Water contains lime.
13	27			A31. Water contains sulfur.
14	31	261	250	
15		265	256	POT(TT).
16		277	275?	POT 273-277 (TT)
17	23			B53.
18	29	259	242	
19	23			A11. Water contains lime.
20		258	248	POT(TT).
21		262	259	POT(TT).
22	32			A10.
23	61			B42. Water contained sulfur for 3 years.
24	24	253	242	
25	12			A8. Water contains lime.

Well	Depth	Elev.	Pot.	Notes
26	38			
27	37	253	241	
28	37	259	242	
29	26			B52.
30	33	262	255	
31	37	261	258	
32	32	270	264	
33	23	245	242	
34	12			A9. Water contains lime.
35	31	253	251	
36		265	245	POT(TT).
37	36	259	241	
38	53	268	255	
39	9			A16. Water contains lime.
40	37			B46.
41	17	258	253	
42	37	273	272	B50. Water contains white sulfur. Well not in use. Depth (M).
43	41	259	253	B2. Water level 6m below surface Feb. 17, 1945 POT(H).
44	34	259	244	
45	41			A17. Dry.
46	31	277	266	
47	15			A18. Water contains lime.
48				A19. Dry.
49				B44.
50	16	251	248	
51	19	256	246	
52	6			A20. Water contains lime.
53	24			B45. Water contains some black sulfur.
54	41	270	259	
55	43	258	252	
56	42	268	249	B47. Water contains sulfur. Depth 30+(H).
57	32	264	247	B43. Water contains some sulfur. Depth 30+(H).
58	26	261	252	
59	42	264	245	
60	25	259	251	
61	25			B48. Water contained sulfur for 5 years; good now.
62	16	262	259	
63	33	265	246	A21. Water contains sulfur.
64	19	255	252	
65	24			B49. Water contains some sulfur.

Well	Depth	Elev.	Pot.	Notes
66	27	251	249	
67	24			A7.
68	23			C14.
69	20	262	247	
70	24			B1. Yield 0.3 l/s.
71	24			C12.
72	34	278	255	
73	29	259	253	
74	39	270	251	
75	18			D9. Water contains sulfur.
76	30	270	258	
77	36	270	255	
78	36?	273	249	
79	40	273	265	
80	61	283	247	
81	5	267	264	D5. Water contains lime. Water level 3m. POT(H).
82	36			D8. Water contains sulfur.
83	39	267	247	
84	46			D4. Well abandoned.
85	21	277	273	
86	46			D3. Well abandoned.
87	26	256	256	
88	24			D2. Well abandoned.
89	35			D6. Well not in use. Water contains sulfur.
90	9	259	257	
91	6	271	266	D1. Water level 5 m below surface Feb. 16, 1945, dry in summer. POT(H).
92	40			D7. Water contains sulfur.
93	41			C18. Yield 0.2-0.3 l/s
94	41			C21. Dry.
95	44			C22. Dry.
96	37	274	268	
97	35	265	266	
98	41			C20. Dry.
99	2	268	267	
100	61			C19. Dry. Well abandoned after drilling, Produced gas.
101	45	274	250	
102	33	270	269	
103	23			Yield adequate for power pump (PH). Depth (PH).
104	30	274	272?	
105	17	270	260	

Well	Depth	Elev.	Pot.	Notes
106	34	262	259	
107	24	268	266	
108	67	280	283?	POT (or elevation) obviously incorrect (JT).
109	44	264	263	
110	18	288	255	
111	6			C29. Water contains lime.

APPENDIX 6 - UNIT CONVERSIONS

LT Coordinates to Latitude and Longitude

As stated in section A2, locations in this report are given in inches on 1:24000 topographic maps east and north of the southwest corner of 2.5 minute quadrangles. These are termed the LT coordinates of the point and, because the map dimensions of each 2.5 minute quadrangle is so nearly constant throughout the Inner Bluegrass Karst Region, the latitude and longitude of the point may be easily calculated. Although the east-west dimensions increase slightly from north to south, the amount of increase is less than the printing variation on the various topographic maps, and the dimensions of all 2.5 minute quadrangles are taken to be 6.00 inches east-west by 7.58 inches north-south. Accordingly, longitude difference in minutes = map inches x .417 and latitude difference in minutes = map inches x .330. The longitude of a point is thus the longitude of the southwest corner minus the longitude difference calculated, and the latitude of the point is the latitude of the southwest corner plus the latitude difference.

As an example, the LT coordinates of Russell Cave Spring are CENV SC 3.44 0.70. The longitude of the southwest corner of the south-central 2.5 minute quadrangle on the Centerville quadrangle is $84^{o}27.5$; and the longitude difference is 3.44 inches x .417 = 1.43 minutes. Hence the longitude of the spring is $84^{o}27.5' - 1.43' = 84^{o}26.07'$. A similar calculation using the latitude of the southwest corner ($38^{o}7.5'$) and the latitude difference (0.70 inches x .330 = 0.23 minutes) yields the latitude of the spring as $38^{o}7.73'$ ($38^{o}7.5' + 0.23'$). The latitude and longitude of Russell Cave Spring is thus $38^{o}7.73'$N, $84^{o}26.07'$W.

Conversion Factors for Units Used

Distance and Length

Multiply kilometers (km) by 0.621 to convert to miles.
" " 3280 " feet.
" meters (m) by 3.28 to convert to feet.
" centimeters (cm) by 0.394 to convert to inches.
" millimeters (mm) by 0.0394 to convert to inches.

Mass and Weight

Multiply kilograms (kg) by 2.20 to convert to pounds.
" grams (g) by 0.0353 to convert to ounces.

Area

Multiply square kilometers (km^2) by 0.386 to convert to square miles.
" square meters (m^2) by 10.8 to convert to square feet.

Volume

Multiply cubic meters (m^3) by 35.3 to convert to cubic feet.

Velocity

Multiply meters per second (m/s) by 53.7 to convert to miles per day.
" " 2.24 " miles per hour.
" " 11800 " feet per hour.
" " 197 " feet per minute.

Discharge

Multiply liters per second (l/s) by 22800 to convert to gallons per day.
" " 0.0353 " cubic feet per second
" " 15.9 " gallons per minute

Gradient

Multiply meters per kilometer (m/km) by 0.100 to convert to percent.
" " 5.28 " feet per mile.
" dimensionless gradient by 100 to convert to percent.
" " 5280 " feet per mile.

Temperature

Multiple degrees Celcius (°C) by 1.80 and add 32.0 to convert to degrees Farenheit.